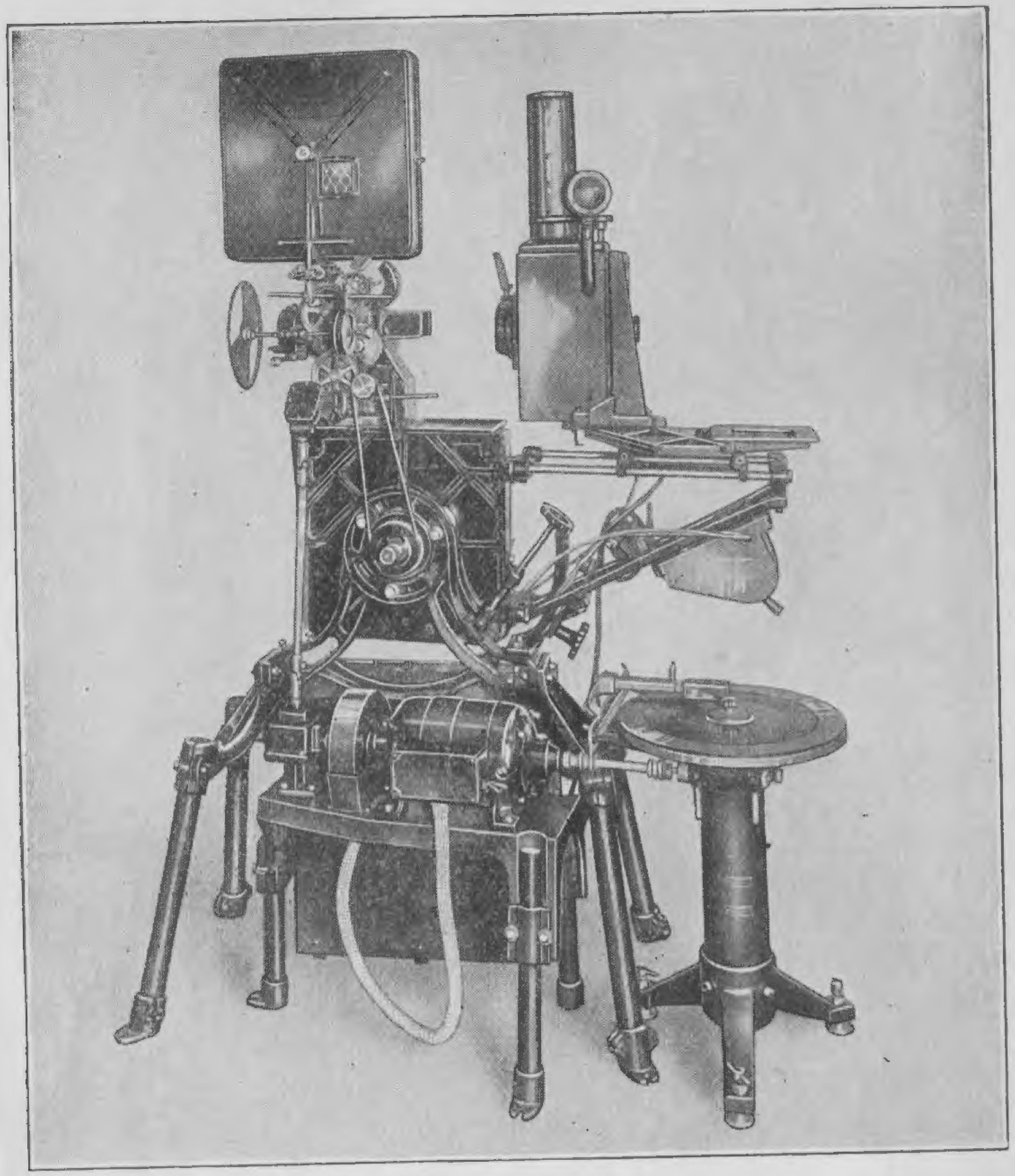
ELEMENTS OF PHYSICS

MILLIKAN AND GALE



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ELEMENTS OF PHYSICS

BY

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BEING A REVISION OF THE AUTHORS' "PRACTICAL PHYSICS" DONE IN COLLABORATION WITH

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PREFACE

Never in the history of the world has any subject grown so rapidly, or changed so radically, as has physics during the past thirty years. A field which used to be thought dry is now attracting universal interest. The authors have perhaps been unusually favorably situated, both for appreciating the changes and for estimating their bearing upon the elementary presentation of the subject. In the preparation of this book they have endeavored to eliminate everything that is outgrown, without sacrificing any of the invaluable and otherwise unattainable results of twenty years of experience, not merely by themselves but by the tens of thousands of physics teachers who have assisted them in their efforts to improve the teaching of physics.

Their chief aim from the beginning has been "*to present elementary physics in such a way as to stimulate the pupil to do some thinking on his own account about the hows and the whys of the physical world in which he lives.*"

Hence as to *subject matter* they have included in this book only such subjects as touch closely the everyday life of the average pupil. In a word, they have endeavored to make it represent the everyday physics which the average person needs to help him to adjust himself to his surroundings, and to interpret his own experiences correctly.

As to *method* they have endeavored to present a systematic, carefully chosen, and well-tested *course* as distinct from an encyclopedic array of heterogeneous facts. This course, in its shortest form, is carried by the larger print. It represents the indispensable backbone of such a presentation as would generally be given in schools which have the least time to spend on physics. It is not too difficult to be

given, if desired, in the second year of the high school, and the problems, the real heart of any course, have been especially chosen and especially tested for such use.

For schools that have more time and can do the work more thoroughly there is provided the course represented by both the large print and the smaller print, with an abundance of additional problems in the Appendix.

In addition to these two systematic courses, and as an aid to both of them, the pedagogical expedient, already successfully tried in a much less complete way, has been adopted of presenting *an incidental picture course on the history of physics* both as to outstanding industrial appliances and as to the "heroes of physics" whose work has made these possible and whose lives lend to the whole subject intense human interest. This consists of ninety-nine full-page illustrations with rather elaborate explanatory legends. No attempt has been made to make these illustrations an organic part of the systematic course presented in the remaining pages. They are introduced rather for the sake of arresting the student's attention, stimulating his interest, and getting before him *incidentally* a large number of fascinating facts and developments, which he will often not understand fully, but which will nevertheless stimulate him to further studies, and give him problems of his own to work upon. The pupil who is capable of doing more and understanding better than the average run of a class should profit greatly by this feature.

A second advantage that offers arises from the fact that almost every teacher has some practical industrial development in which he is especially interested, and which, often for local reasons, he wishes to incorporate into his course, sometimes even when it is beyond the proper scope of an elementary course organized for the average pupil. Such a teacher can incorporate as many of the full-page inserts into his own systematic course as he wishes.

Another new pedagogical expedient for us is the introduction of brief, telling summaries at frequent intervals for the sake of giving the pupil condensed reviews as to just what the discussion has been about and what are the important results. These have been done with very great care and should be an important aid in the simplification of the subject, and in rendering it coherent and intelligible. A further step in the same direction has been taken in the elimination of some problems and some subjects which experience has shown to be rather beyond the abilities of the average high-school pupil of today.

Acknowledgments are due literally to thousands of teachers who have assisted us by trying out in the school of experience not merely our methods but our actual mode of presentation. We have had especial assistance of this sort from Edward E. Ford, West High School, Rochester, New York; Allan Peterson, East High School, Des Moines, Iowa; Willis C. Campbell, Gorton High School, Yonkers, New York; Walter L. Barnum, Evanston High School, Evanston, Illinois; E. Waite Elder, East High School, Denver, Colorado, who has in addition read all the proof; Charles F. Dutton, West High School of Commerce, Cleveland, Ohio; Dr. Hugh Dunn, Bell Telephone Laboratories, who has given us invaluable assistance on the radio sections; and E. A. Merrill of the California Institute of Technology, who has assisted in developing a new and very simple presentation of the principles of the airplane.

R. A. M.
H. G. G.
W. R. P.

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ELEMENTS OF PHYSICS

CHAPTER I

MEASUREMENT

Fundamental Units

1. Introductory. A certain amount of knowledge about familiar things comes to us all very early in life. We learn almost unconsciously, for example, that stones sink in water, whereas wood floats; that the teakettle stops boiling when removed from the fire; that we wait, after a lightning flash, to hear the thunder; that telephone messages travel by electric currents; etc. The aim of the study of physics is to set us to thinking about *how* and *why* such things happen and, to a less degree, to acquaint us with other happenings which we may not have noticed or heard of previously.

Our accurate knowledge about natural phenomena has been acquired chiefly through careful measurements. We can measure three fundamentally different kinds of quantities, — length, mass, and time, — and we shall find that all other measurements may be reduced to these three. Our first problem in physics is, then, to learn something about the units in terms of which all our physical knowledge is expressed.

2. The historic standard of length. Nearly all civilized nations have at some time employed a unit of length the name of which bore the same significance as does *foot* in English. There can scarcely be any doubt, therefore, that in each country this unit has been derived from the length of the human foot. The *yard* is supposed to have represented

the length of the arm of an English king, Henry I. After this unit became established as a standard, it is probable that the foot was arbitrarily chosen as one third of the yard. In view of such an origin it will be clear why no agreement existed among the units in use in different countries.

3. Relations between different units of length. It has also been true, in general, that in a given country the different units of length in common use (such, for example, as the inch, the hand, the foot, the fathom, the rod, the mile, etc.) have been derived either from the lengths of different members of the human body or from equally unrelated magnitudes, and in consequence have been connected with one another by different, and often by very awkward, multipliers. Thus, there are 12 inches in a foot, 3 feet in a yard, $5\frac{1}{2}$ yards in a rod, 1760 yards in a mile, etc.

4. Relations between units of length, area, volume, and mass. A similar and even worse complexity exists in the relations of the units of length to those of area, volume, and mass. Thus, there are $272\frac{1}{4}$ square feet in a square rod, $57\frac{3}{4}$ cubic inches in a quart, and $31\frac{1}{2}$ gallons in a barrel. Again, the pound, instead of being the mass of a cubic inch or a cubic foot of water, or of some other common substance, is the mass of a cylinder of platinum, of inconvenient dimensions, which is preserved in London.

5. Origin of the metric system. At the time of the French Revolution the extreme inconvenience of existing weights and measures, together with the confusion arising from the use of different standards in different localities, led the National Assembly of France to appoint a commission to devise a more logical system. The result of the labors of this commission was the present metric system, which was introduced into France in 1793 and has since been adopted by the governments of most civilized nations except those of Great Britain and the United States; and even in these countries its use in scientific work is practically universal. The World War did much to speed its adoption in these countries.

6. The standard meter. The standard *length* in the metric system is called the *meter* (m.). It is the distance, at the freezing temperature, between two transverse parallel lines

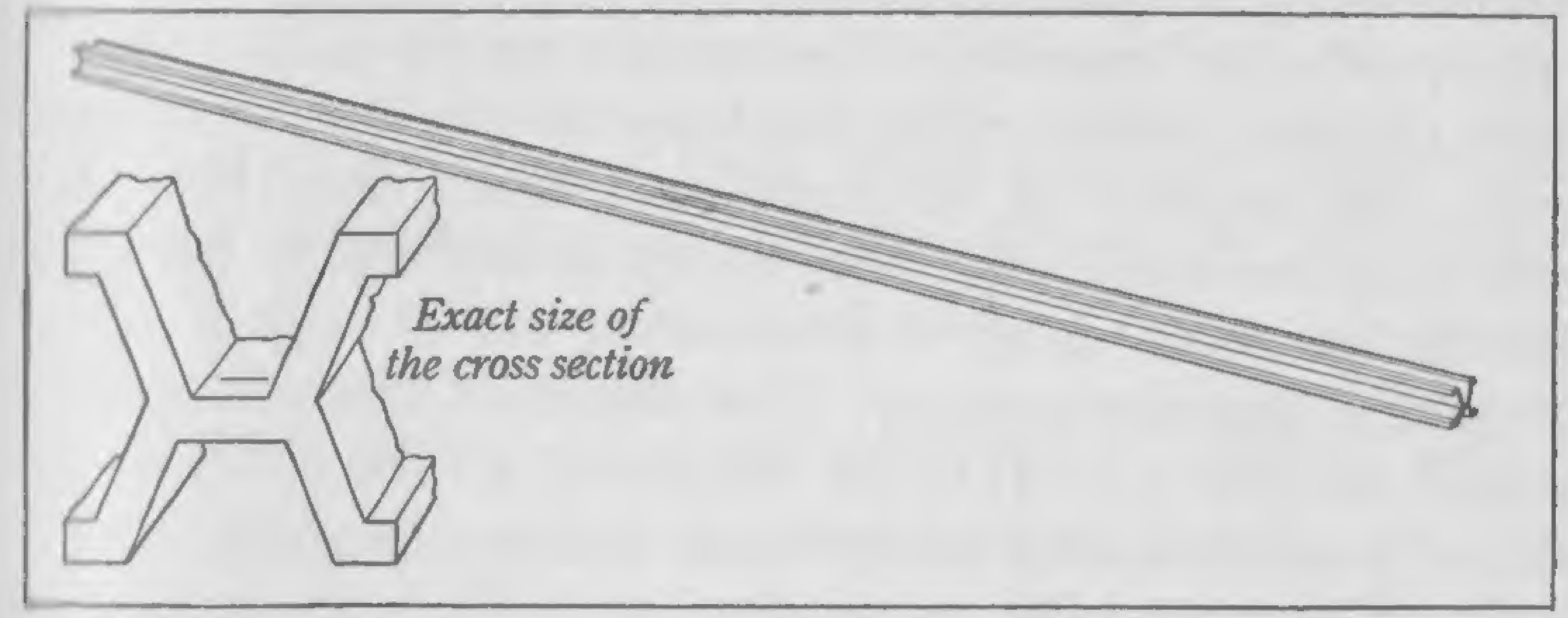


FIG. 1. The standard meter

ruled on a bar of platinum-iridium (Fig. 1), which is kept at the International Bureau of Weights and Measures at Sèvres, near Paris. *This distance is 39.37 inches* (Fig. 2).

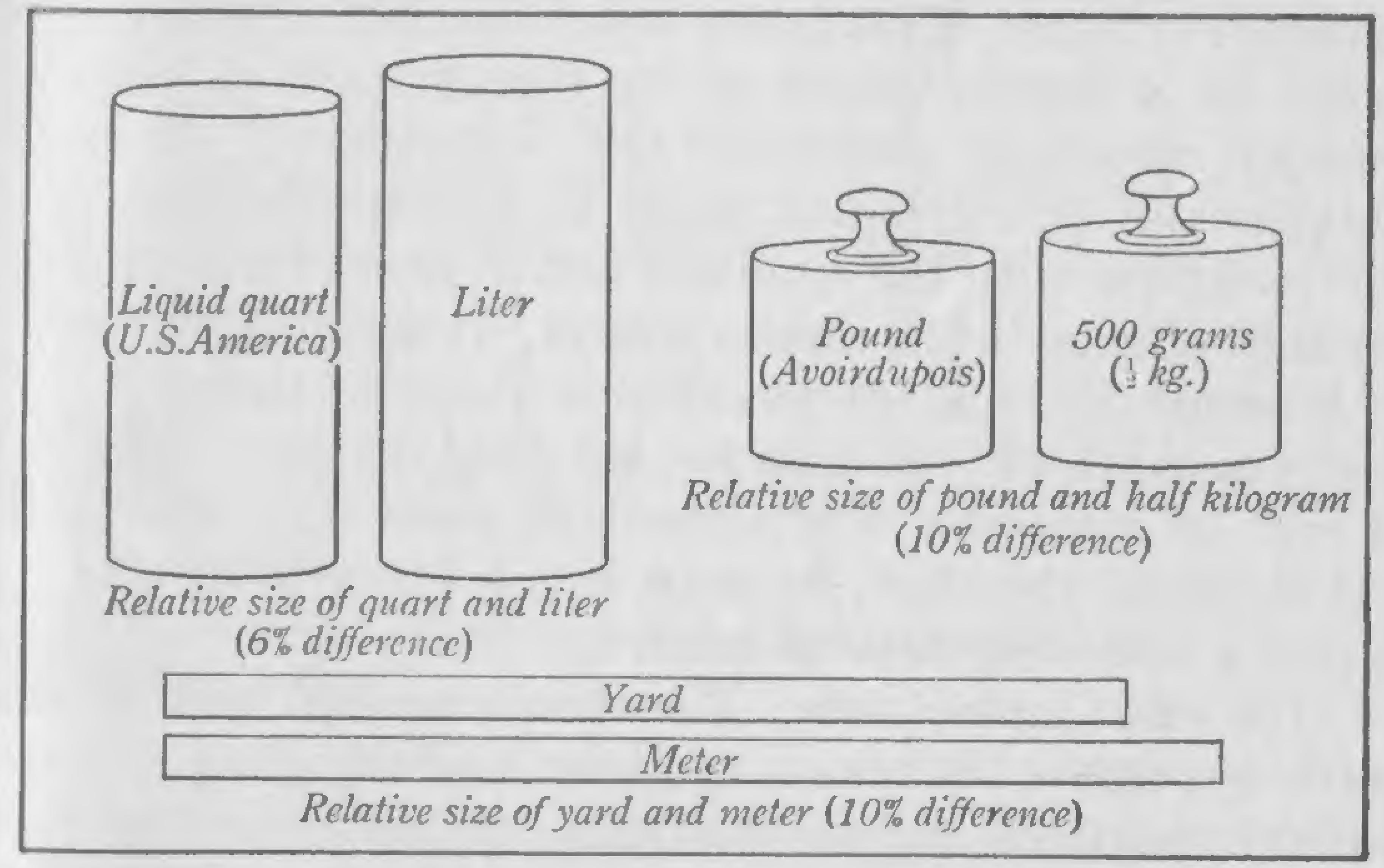


FIG. 2. Metric units in comparison with the old unstandardized units

In order that this standard length might be reproduced if lost, the commission attempted to make it one ten-millionth

of the distance from the equator to the north pole, measured on the meridian of Paris. But since later measurements have thrown some doubt upon the exactness of the commission's determination of this distance, we now define the meter not as any particular fraction of the earth's quadrant, but simply as the distance between the scratches on the bar mentioned above. On account of its more convenient size the centimeter (one one-hundredth of a meter) is universally used, for scientific purposes, as the fundamental unit of length.

7. Metric standard capacity. The standard unit of capacity is called the *liter* (l.). It is the volume of a cube which is one tenth of a meter (about 4 inches) on a side. *The liter is therefore equal to 1000 cubic centimeters* (cc.). It is equivalent to 1.057 quarts. A liter and a quart are therefore roughly equivalent measures (Fig. 2).

8. The metric standard of mass. In order to establish a connection between the unit of length and the unit of mass, the commission directed a committee of the French Academy to prepare a cylinder of platinum which should have the same weight as a liter of water at its temperature of greatest density; namely, 4° centigrade (39° Fahrenheit). An exact equivalent of this cylinder, made of platinum-iridium and kept at Sèvres with the standard meter, now represents the standard of mass in the metric system. It is called the *standard kilogram* (kg.) and is equivalent to about 2.2 pounds. One one-thousandth of this mass was adopted as the fundamental unit of mass and was named the *gram* (g.). For practical purposes, therefore, *the gram may be taken as equal to the mass of 1 cubic centimeter of water.*

9. The other metric units. The three standard units of the metric system — the meter, the liter, and the gram — have decimal multiples and submultiples, so that every unit of length, volume, or mass is connected with the unit of next higher denomination by an invariable multiplier; namely, ten.

The names of the multiples are obtained by adding the Greek prefixes *deka* (ten), *hecto* (hundred), *kilo* (thousand);

the submultiples are formed by adding the Latin prefixes *deci* (tenth), *centi* (hundredth), and *milli* (thousandth). Thus:

1 dekameter = 10 meters	1 decimeter = $\frac{1}{10}$ meter
1 hectometer = 100 meters	1 centimeter = $\frac{1}{100}$ meter
1 kilometer = 1000 meters	1 millimeter = $\frac{1}{1000}$ meter

The most common of these units, with the abbreviations which will be used for them in this book, are the following:

meter (m.)	millimeter (mm.)	gram (g.)
kilometer (km.)	liter (l.)	kilogram (kg.)
centimeter (cm.)	cubic centimeter (cc.)	milligram (mg.)

10. Relations between the English and metric units. The following table, *which is inserted for reference only*, gives the relation between the most common English and metric units:

1 inch (in.) = 2.54 cm.	1 cm. = .3937 in.
1 foot (ft.) = 30.48 cm.	1 m. = 1.094 yd. = 39.37 in.
1 mile (mi.) = 1.609 km.	1 km. = .6214 mi.
1 grain = 64.8 mg.	1 g. = 15.44 grains
1 oz. av. = 28.35 g.	1 g. = .0353 oz.
1 lb. av. = .4536 kg.	1 kg. = 2.204 lb.

The relations 1 in. = 2.54 cm., 1 m. = 39.37 in., 1 kilo (kg.) = 2.2 lb., 1 km. = .62 mi., should be memorized. Portions of a

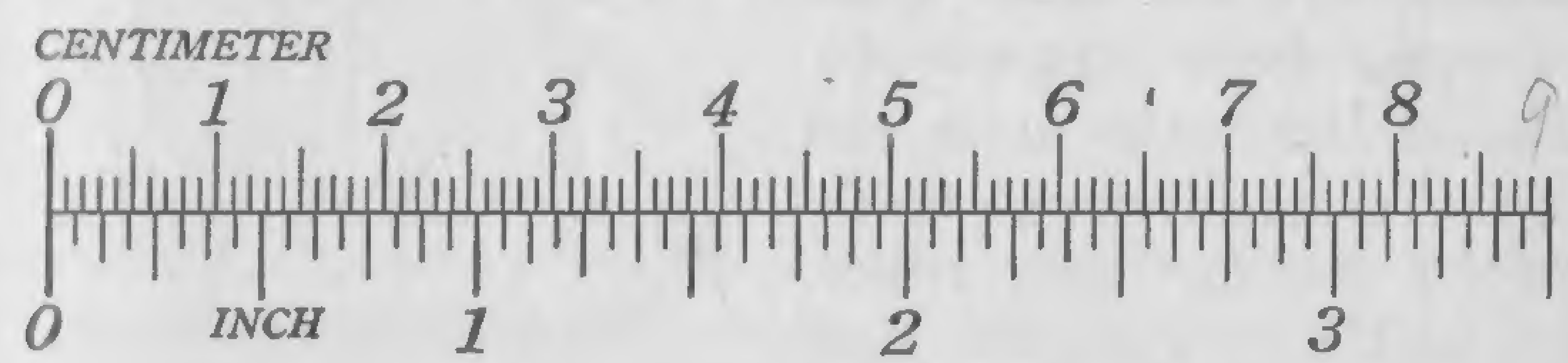


FIG. 3. Centimeter and inch scales

centimeter and of an inch scale are shown together in Fig. 3. It will be seen from Fig. 3 that 1 inch = 2.54 centimeters.

11. The standard unit of time. The *second* is taken among all the civilized nations as the standard unit of time. It is $\frac{1}{86400}$ part of the time from noon to noon; that is, of the mean solar day.

12. Measurement of length. Measuring the length of a body consists simply in comparing its length with that of the standard meter bar kept at the International Bureau. In order that this may be done conveniently, great numbers of rods of the same length as this standard meter bar have been made and distributed all over the world. They are our common meter sticks. They are divided into 10, 100, or 1000 equal parts. Great care is taken to have all the parts of exactly the same length.

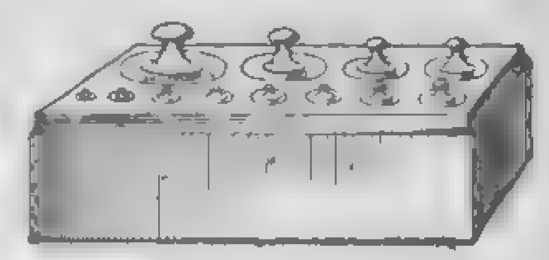


FIG. 4. A set of weights

13. Measurement of mass. Similarly, measuring the mass of a body consists in comparing its mass with that of the standard kilogram. In order that this might be done conveniently it was first necessary to construct bodies of the same mass as this kilogram, and then to make a whole series of bodies whose masses were $\frac{1}{2}$, $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$, etc. of the mass of this kilogram; in other words, to construct a set of standard masses commonly called a *set of weights* (Fig. 4).

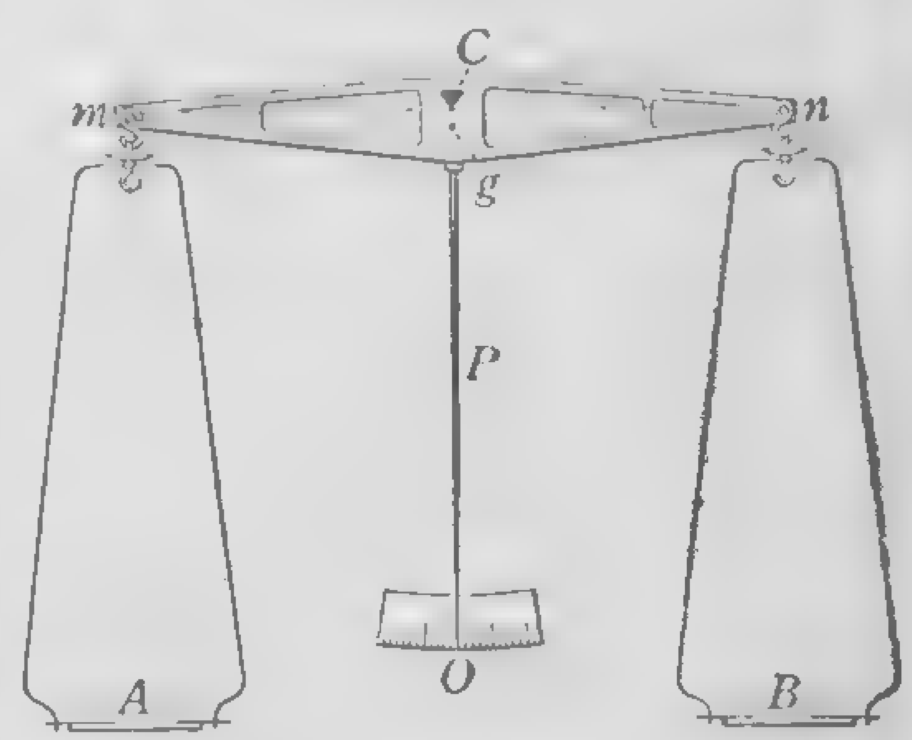


FIG. 5. The simple balance

With the aid of such a set of standard masses the determination of the mass of an unknown body is made by placing the body upon the pan *B* (Fig. 5), counterpoising by adding shot, paper, etc. to the pan *A*, and then replacing the unknown body at *B* by as many of the standard masses as are required to bring the pointer back to *O* again. The mass of the body is equal to the sum of these standard masses. This rigorously correct method of weighing is called the *method of substitution.*

If a balance is well constructed, however, a weighing may usually be made with sufficient accuracy by simply placing the unknown body upon one pan and finding the sum of the

standard masses which must then be placed upon the other pan to bring the pointer again to *O*. This is the usual method of weighing. It gives correct results, however, only when the knife-edge *C* is exactly midway between the points of support *m* and *n* of the two pans. The method of substitution, on the other hand, is independent of the position of the knife-edge. *It is customary to consider that the mass of a body determined as here treated is a measure of the quantity of matter which it contains.*

SUMMARY. The three fundamental measuring instruments are (1) the meter, to measure *lengths*; (2) the balance, to measure *masses*; (3) the clock, to measure *times*.

1 m. = 39.37 in.; 1 in. = 2.54 cm.; 1 km. = .62 mi.; 1 l. = 1000 cc. = about 1 qt.; 1 kg. = mass of 1 l. of water at 4° C. = about 2.2 lb.

QUESTIONS AND PROBLEMS

1. Name as many advantages as you can which the metric system has over the English system. Can you think of any disadvantages?

2. Find the number of millimeters in 6 km. Find the number of inches in 4 mi. Which is the easier to do?

3. A new lead pencil is 7 in. long. How many centimeters long is it?

4. The Twentieth Century Limited runs from New York to Chicago (967 mi.) in 20 hr. Find its average speed in kilometers per hour.

5. With a Vickers-Vimy biplane Captain Alcock and Lieutenant Brown completed, on June 15, 1919, the first nonstop transatlantic flight of 1890 miles from Newfoundland to Ireland in 15 hr. 57 min. How many miles did they travel per hour? How many kilometers per hour?

6. From the bed rock upon which the Woolworth Building in New York rests to the top of the tower is 278.3 m. How many feet is it?

7. What must you do to find the capacity in liters of a box when its length, breadth, and depth are given in meters? to find the capacity in quarts when its dimensions are given in feet?

8. Find the capacity in liters of a box .5 m. long, 20 cm. wide, and 100 mm. deep.

9. How many kilograms are there in the 16-pound shot?

10. If you bought a metric ton (= 1000 kg.) of coal, how many more pounds should you have to pay for than if you had bought an English ton?

Density

14. Definition of density. When equal volumes of different substances, such as lead, wood, iron, etc., are weighed in the manner described above, they are found to have widely different masses. The term "density" is used to denote the *mass, or quantity of matter, per unit volume.*

Thus, for example, in the English system the cubic foot is the unit of volume, and the pound is the unit of mass. Since 1 cubic foot of water is found to weigh 62.4 pounds, we say that in the English system *the density of water is 62.4 pounds per cubic foot.*

In the centimeter-gram-second (C.G.S.) system the cubic centimeter is taken as the unit of volume, and the gram as the unit of mass. Hence we say that in this system the density of water is 1 gram per cubic centimeter, for it will be remembered that the gram was taken as the mass of 1 cubic centimeter of water. Unless otherwise expressly stated, density is now universally understood to signify density in C.G.S. units; that is, *the density of a substance is the mass in grams of 1 cubic centimeter of that substance.*

The density of some of the most common substances is given in the following table:

DENSITIES OF SOLIDS

(In grams per cubic centimeter)

Pine	.5	Copper	8.9
Oak	.8	Nickel	8.9
Ice	.9	Silver	10.5
Aluminum	2.58	Lead	11.3
Glass	2.6	Gold	19.3
Zinc	7.1	Tungsten	19.6
Iron (cast)	7.4	Platinum	21.4
Brass	8.5	Osmium	22.5

DENSITIES OF LIQUIDS

(In grams per cubic centimeter)

Gasoline	.75	Hydrochloric acid	1.27
Alcohol	.79	Carbon bisulphide	1.29
Glycerin	1.26	Mercury	13.6

15. Relation between mass, volume, and density. Since the mass of a body is equal to the total number of grams which it contains, and since its volume is the number of cubic centimeters which it occupies, the mass of 1 cubic centimeter is evidently equal to the total mass divided by the volume. Thus, if the mass of 100 cubic centimeters of iron is 740 grams, the density of iron must equal $740 \div 100 = 7.4$ grams to the cubic centimeter. To express this relation in the form of an equation, let M represent the mass of a body, that is, its total number of grams; V its volume, that is, its total number of cubic centimeters; and D its density, that is, the number of grams in 1 cubic centimeter; then

$$D = \frac{M}{V}. \quad (1)$$

This equation merely states the definition of density in algebraic form.

16. Distinction between density and specific gravity. The term "specific gravity" is used to denote *the ratio between the weight of a body and the weight of an equal volume of water.**

Thus, if a certain piece of iron weighs 7.4 times as much as an equal volume of water, its specific gravity is 7.4. But since the density of water in C.G.S. units is 1 gram per cubic centimeter, the density of iron in that system is 7.4 grams per cubic centimeter. It is clear, then, that *density in C.G.S. units is numerically the same as specific gravity.*

Specific gravity is the same in all systems, since it is simply the number obtained by dividing the weight of a body by

* For the present purpose the terms "weight" and "mass" may be used interchangeably. They are in general numerically equal, although an important distinction between them will be developed in § 73. Weight is, in reality, a *force* rather than a *quantity of matter.*

the weight of an equal volume of water. Density, however, which we have defined as the mass per unit volume, is different in different systems. Thus, in the English system the density of iron (which in the metric system is 7.4 grams per cubic centimeter) is 462 pounds per cubic foot (7.4×62.4), since we have found that water weighs 62.4 pounds per cubic foot and that iron weighs 7.4 times as much as an equal volume of water.*

SUMMARY. The density of a substance is its mass per unit volume. Expressed as a formula,

$$D = \frac{M}{V}.$$

The specific gravity of a substance is the ratio between the weight of any volume of the substance and the weight of an equal volume of water.

The density of a substance in C.G.S. units is numerically equal to its specific gravity.

The density of a substance expressed in pounds and cubic feet is numerically 62.4 times its specific gravity.

QUESTIONS AND PROBLEMS †

1. A ball of yarn is squeezed into one fourth its original bulk. What effect does this produce on its mass? on its volume? on its density?

2. Name three uses made of lead because of its great density, and two uses made of cork because of its small density.

3. A liter of milk weighs 1032 g. What is its density? its specific gravity?

4. How many cubic centimeters are there in a block of brass weighing 34 g.? (See table of densities, p. 8.)

5. What is the mass of a liter of alcohol? (See table, p. 9.)

6. A flask holds 2520 g. of glycerin when filled. What is the capacity of the flask in liters?

* Laboratory exercises on length, mass, and density measurements should accompany or follow this chapter. See, for example, Experiments 1, 2, and 3 of "Exercises in Laboratory Physics" by Millikan, Gale, and Davis.

† Supplementary questions and problems for Chapter I are given in the Appendix.

7. If a wooden beam is $30 \times 20 \times 500$ cm. and has a mass of 150 kg., what is the density of the wood? What is its density in the English system?

8. A contractor has to remove 1000 slabs of marble, each 2 in. thick, 12 in. wide, and 6 ft. long. How many tons must he remove, marble having a specific gravity of 2.7?

9. A piece of gold weighs 772 g. Find the weight of a piece of lead having a volume equal to that of the gold.

CHAPTER II

PRESSURE IN LIQUIDS

Liquid Pressure beneath a Free Surface

17. Definition of pressure. We are all conscious of the fact that in order to lift a kilogram of mass we must exert an upward pull. Experience has taught us that the greater the mass, the greater the force which we must exert. The force is commonly taken as numerically equal to the mass lifted. This is called the *weight measure* of a force. *A push or pull which is equal to that required to support a gram of mass is called a gram of force.* Thus, five grams of force are needed to lift a new five-cent piece. *Pressure is defined as the force per unit area.*

18. Force beneath the surface of a liquid. When a piece of cork is released below the surface of water, it is immediately forced up to the surface, where it floats. An ocean liner, although constructed of steel and weighing thousands of tons, is supported by the upward force of the water against the bottom of the ship. Street water mains which are far below the level of the water in the reservoir not infrequently burst from the force of the water.

To investigate the nature of the forces beneath the free surface of a liquid, we shall use a pressure gauge of the form shown in Fig. 6. If the rubber diaphragm which is stretched across the mouth of a thistle tube A is pressed in lightly with the finger, the top B of the column of colored water will be observed to move upward in the tube T, but it will return to its first position as soon as the finger is removed. If the pressure of the finger is increased, the column will rise a greater distance than before. We may therefore take the amount of motion of the column as a measure of the force acting on the diaphragm.

Now let A be pushed down first 10 cm., then 20 cm., then 30 cm. below the surface of the water (Fig. 6). The motion of the index B will show that the upward force continually increases as the depth increases.

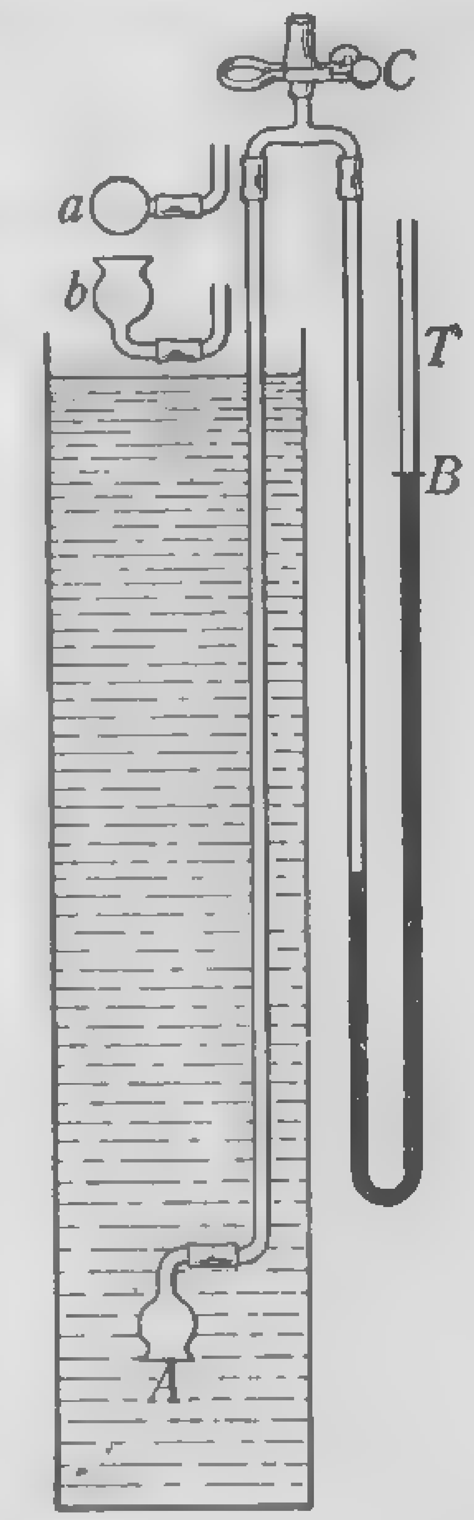


FIG. 6. Gauge for measuring liquid pressure

Careful measurements made in the laboratory will show that *the force is directly proportional to the depth.**

Let the diaphragm A (Fig. 6) be pushed down to some convenient depth (for example, 10 cm.) and the position of the index be noted by a little rubber ring cut from a piece of tubing. Then let it be turned sidewise so that its plane is vertical (see a, Fig. 6), and adjusted in position until its center is exactly 10 cm. beneath the surface; that is, until the *average* depth of the diaphragm is the same as before. The position of the index will show that the force is also exactly the same as before.

Let the diaphragm then be turned to the position b, so that the gauge measures the *downward* force at a depth of 10 cm. The index will show that this force is again the same.

We conclude, therefore, that *at a given depth a liquid presses up and down and sidewise on a given surface with exactly the same force.*

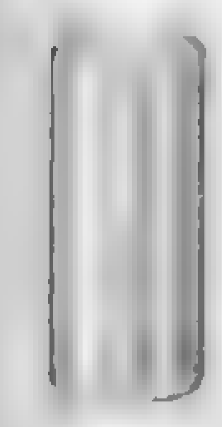


FIG. 7

19. Magnitude of the force. If a vessel like that shown in Fig. 7 is filled with a liquid, the force against the bottom is obviously equal to the weight of the column of liquid resting upon the bottom. Thus, if F represents this force in grams, A the area in square centimeters, h the depth in centimeters, and d the density in grams per cubic centimeter, we shall have

$$F = Ahd. \tag{1}$$

* It is recommended that quantitative laboratory work on the law of depths and on the use of manometers accompany this discussion. See, for example, Experiment 4 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

Similarly, the force will be computed in pounds if the units used are square feet, feet, and pounds per cubic foot. Since, as was shown by the experiment of the preceding section, the force on a given area is the same in all directions at a given depth, we have the following general rule:

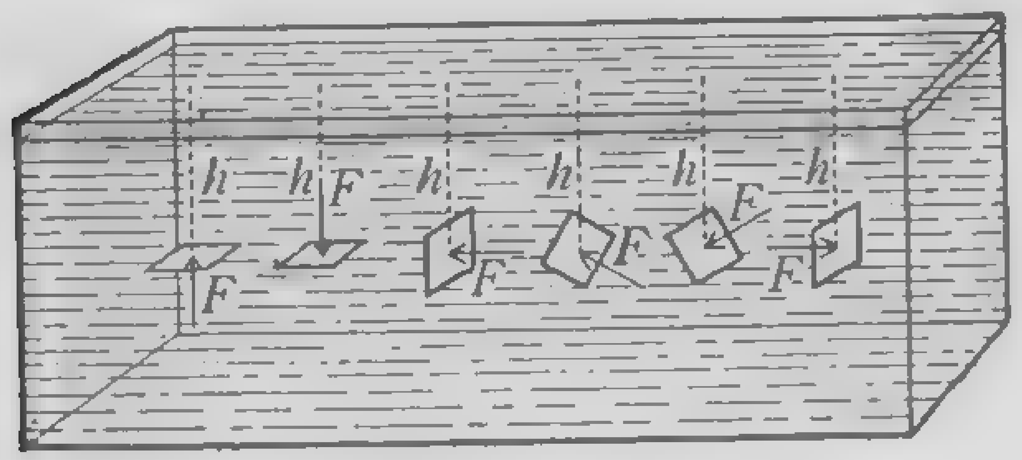


FIG. 8. The average depth, h, is the distance from the free surface to the center of the area

The force which a liquid exerts against any surface is equal to the area of the surface times its average depth times the density of the liquid.

It is important to bear in mind that "average depth," h, means the vertical distance from the level of the free surface to the center of the area in question (Fig. 8).

20. Pressure in liquids. Thus far attention has been confined to the total force exerted by a liquid against the *whole* of a given surface. It is often more convenient to imagine the surface divided into square centimeters or square inches, and then to consider the force on one of these units of area. In physics the word "pressure" is used exclusively to denote the *force per unit area.* Pressure is thus a measure of the *intensity* of the force acting on a surface, and does not depend at all on the area of the surface. Since, by § 19, $F = Ahd$, and since by definition the pressure p is equal to the force per unit area, we have

$$p = \frac{F}{A} = hd. \tag{2}$$

Therefore *the pressure at a depth of h centimeters below the surface of a liquid of density d is hd grams per square centimeter.*

If the height is given in feet and the density in pounds per cubic foot, then the product hd gives the pressure in pounds per square foot. Dividing by 144 gives the result in pounds per square inch.

21. Levels of liquids in connecting vessels. It is a perfectly familiar fact that when water is poured into a teapot it stands at exactly the same level in the spout as in the body of the teapot; or if it is poured into a number of connected vessels like those shown in Fig. 9, the surfaces of the liquid in the various vessels lie in the same horizontal plane. The pressure at c (Fig. 10) was shown by the experiment of § 18 to be equal to the density of the liquid times the depth cg. The pressure at o in the opposite direction must be equal to that at c, since the liquid does not tend to move in either direction. Hence the pressure at o must be cg ($= ks$) times the density; that is, the vertical depth beneath the free surface times the density.

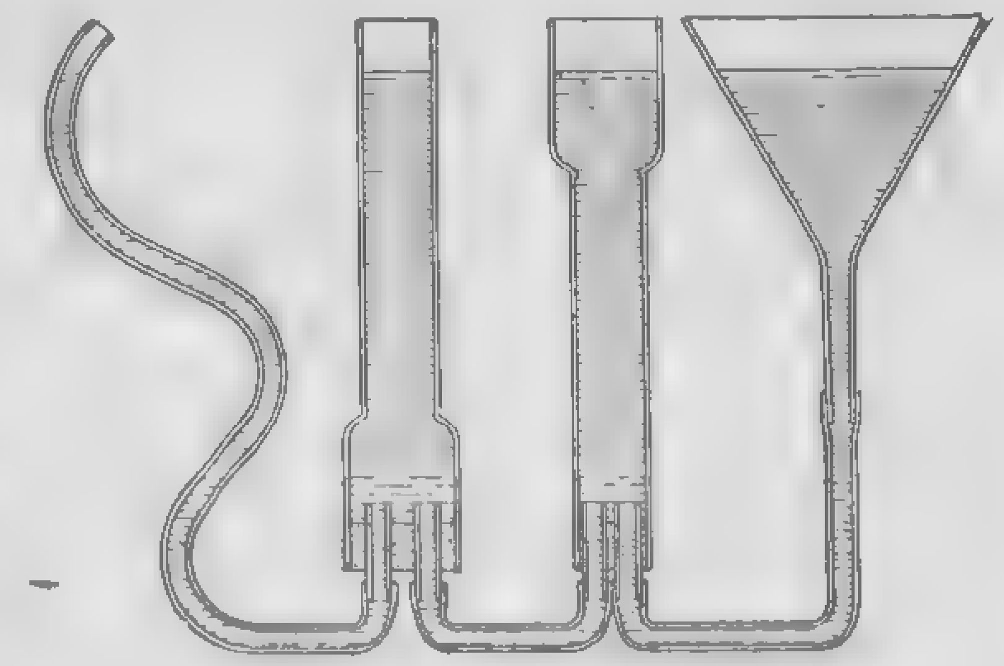


FIG. 9. Water level in communicating vessels

If water is poured in at s so that the height ks is increased, the pressure to the left at o becomes greater than the pressure to the right at c, and a flow of water takes place to the left until the heights are again equal.

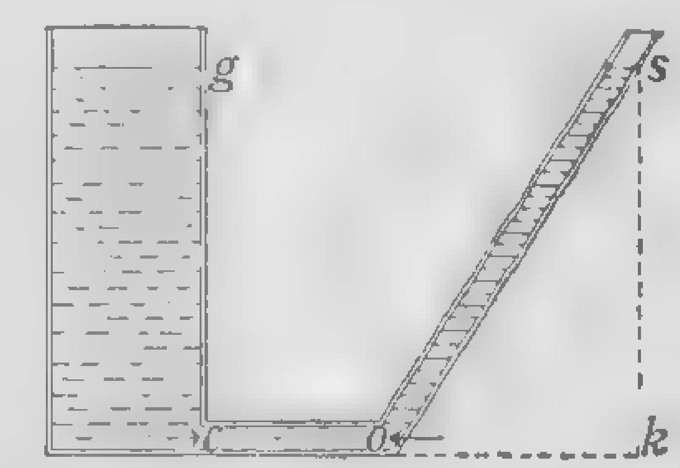


FIG. 10. Why water seeks its level

It follows from these observations on the level of water in connected vessels that *the pressure beneath the surface of a liquid depends simply on the vertical depth beneath the free surface, and not at all on the size or shape of the vessel.*

SUMMARY. A force is a push or a pull. A gram of force is the push or pull which is required to support 1 gram of mass at the earth's surface.

Pressure is force per unit area.

The pressure at a given point within a liquid is the same in all directions.

Pressure, measured in grams per square centimeter, is the vertical depth h below the surface times the density d of the liquid; that is, $p = hd$.

All parts of the free surface of a liquid in the same vessel or in connecting vessels lie in the same horizontal plane.

QUESTIONS AND PROBLEMS

1. A fish swims horizontally across a lake (Fig. 11), as indicated by the dotted line, first in deep water, then in shallow water, and finally under an overhanging rock. How does the force of the water upon the fish compare in the three places? Explain fully.

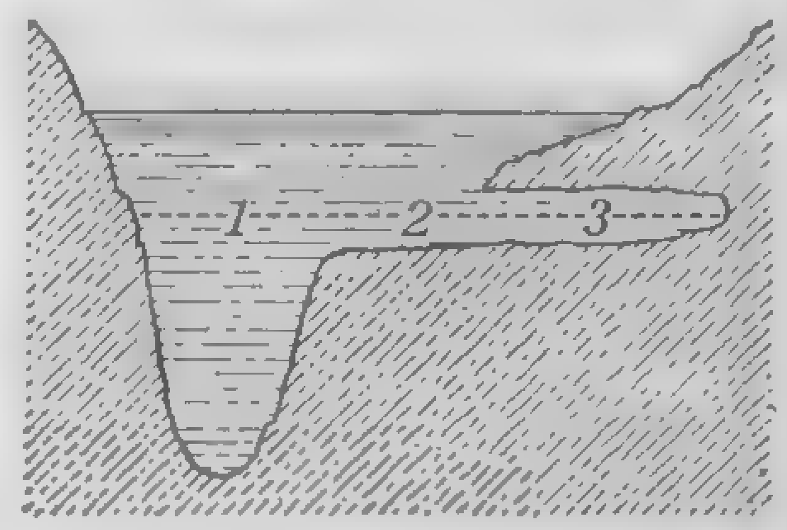


FIG. 11

2. A man weighing 180 lb. is walking on snow. The soles of his shoes are each 30 sq. in. in area. When his entire weight rests on one foot, what *force* does his foot exert on the snow? What *pressure* does it exert? If he uses snowshoes, each having an area of 300 sq. in., what is the pressure of one snowshoe when it supports his entire weight? What is its force? Why do snowshoes sink less in snow than ordinary ones?

3. If the point of a lead pencil has an area of $\frac{1}{5000}$ of a square inch, and you push it against a piece of paper with a force of 2 lb., how great is the pressure?

4. A standpipe 100 ft. high is filled with water. Determine the pressure at the bottom in pounds per square foot and in pounds per square inch.

5. A hole 5 cm. square is made in a ship's bottom 7 m. below the water line. What force in kilograms is required to hold a board above the hole?

6. Kerosene has a density .8 that of water (1 cu. ft. of water = 62.4 lb.). Find the pressure of the kerosene per square foot and per square inch on the bottom of an oil tank filled to a depth of 30 ft.

7. If the water pressure in the city mains is 70 lb. to the square inch, how high above the town is the top of the water in the standpipe?

A HYDRAULIC PRESS

This picture was taken when the press was making a huge hollow forging of steel 52 inches inside diameter, 62 inches outside diameter, and 44 feet long. A mass of red-hot steel weighing 100 tons is being squeezed by the enormous forces of the press out over a solid steel mandrel weighing 87½ tons. The press exerts between its jaws a force of 14,000 tons. This is transmitted to the jaws from two cylinders each 50½ inches in diameter and each sustaining a hydraulic pressure of 7000 pounds per square inch. The huge hollow forgings when completed are used as reaction chambers for the cracking of gasoline. (Courtesy of the Bethlehem Steel Company)

BLAISE PASCAL (1623–1662)

Brilliant French mathematician, physicist, and philosopher. He enunciated the law of transmission of pressure by liquids, showed that the force of a liquid against the bottom of an open vessel is independent of the shape of the vessel, and verified the theory of Torricelli by having a barometer carried to the top of a mountain and the fall of the mercury column noted

8. A swimming tank 50 ft. square is filled with water to a depth of 5 ft. Find the force of the water on the bottom; on a side.

9. Find the total force against the gate of a lock if its width is 60 ft. and the depth of the water 20 ft. Will it have to be made stronger if it holds back a lake than if it holds back a small pond?

10. A U-tube having a cross section of 1 sq. cm. is filled to a certain level with mercury (density 13.6 g. per cubic centimeter). Then 20 cc. of water are poured into one side. What is now the difference in level between the top of the water on one side and the top of the mercury on the other?

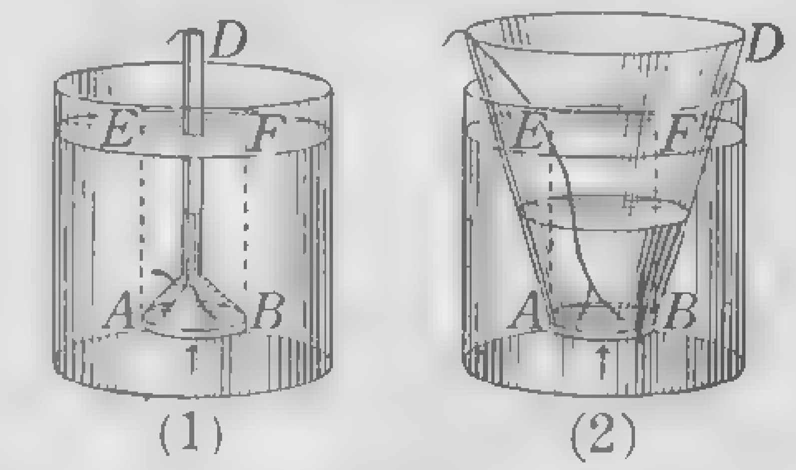


FIG. 12. Illustration of hydrostatic paradox

11. If the areas of the surfaces AB in Fig. 12, (1) and (2), are the same, and if water is poured into each vessel at D till it stands at the same height above AB, how will the downward force on AB in Fig. 12 (2) compare with that in Fig. 12 (1)? Test your answer, if possible, by making AB a piece of cardboard and pouring water in at D, in each case, until the cardboard is forced off.

Pascal's Law

22. Transmission of pressure by liquids. From the fact that pressure within a free liquid depends simply upon the depth and density of the liquid, it is possible to deduce a very surprising conclusion, which was first stated by the famous French scientist, mathematician, and philosopher Pascal (see opposite page).

Let us imagine a vessel of the shape shown in Fig. 13 (1) to be filled with water up to the level ab. For simplicity let the upper portion be assumed to be 1 square centimeter in cross section. Since the density of water is 1, the force with which it presses against any square centimeter of the interior surface which is h centimeters beneath the level ab is h grams. Now let 1 gram of water (that is, 1 cubic centimeter) be poured into the tube. If a given square centimeter of surface was before h centimeters beneath the level of the water

in the tube, it is now $h + 1$ centimeters beneath this level. Therefore the new pressure which the water exerts against it is $h + 1$ grams; that is, applying 1 gram of force to the square centimeter of surface *ab* has added 1 gram to the force exerted by the liquid against each square centimeter of the interior of the vessel. Obviously it can make no difference whether the pressure which was applied to the surface *ab* was due to a weight of water, or to a piston carrying a load, as in Fig. 13 (2), or to any other cause whatever. We therefore arrive at Pascal's conclusion, namely, that *pressure applied anywhere to a body of confined liquid is transmitted undiminished to every portion of the surface of the containing vessel.*

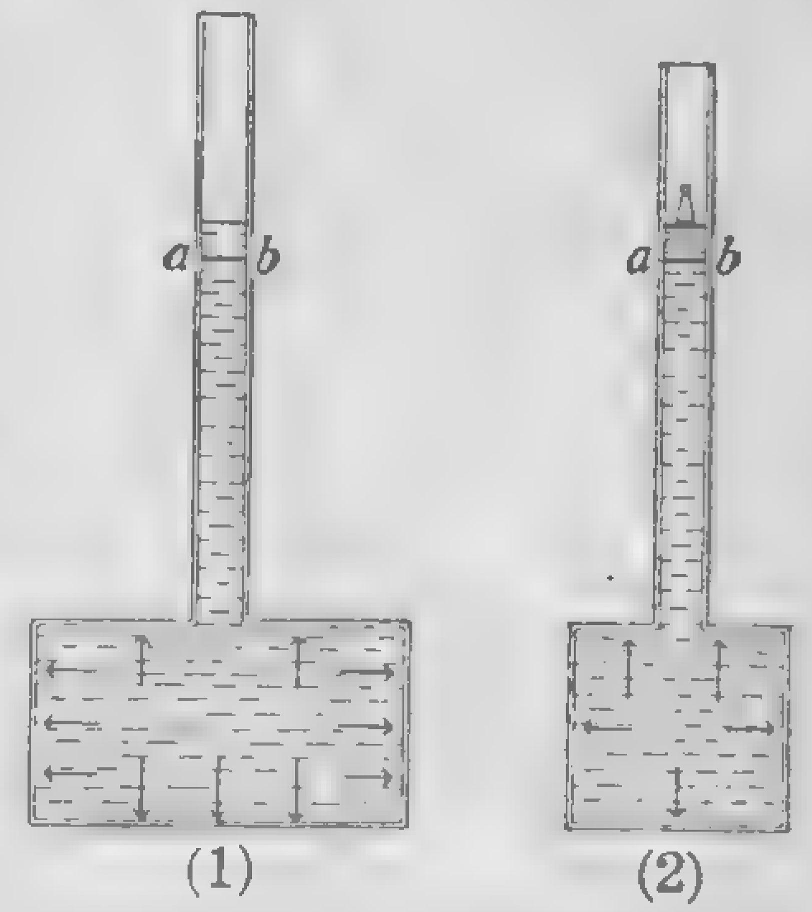


FIG. 13. Proof of Pascal's law

23. Multiplication of force by the transmission of pressure by liquids. Pascal himself pointed out that with the aid of the principle stated above we ought to be able to transform a very small force into one of unlimited magnitude. Thus, if the area of the cylinder *ab* (Fig. 14) is 1 square centimeter, and that of the cylinder *AB* is 1000 square centimeters, a force of 1 kilogram applied to *ab* would be transmitted by the liquid so as to act with a force of 1 kilogram on each square centimeter of the surface *AB*. Hence the total upward force exerted against the piston *AB* by the 1 kilogram applied at *ab* would be 1000 kilograms. Pascal's own words are as follows: "A vessel full of water is a new principle in mechanics, and a new machine for the multiplication of force to any required extent, since one man will by this means be able to move any given weight."

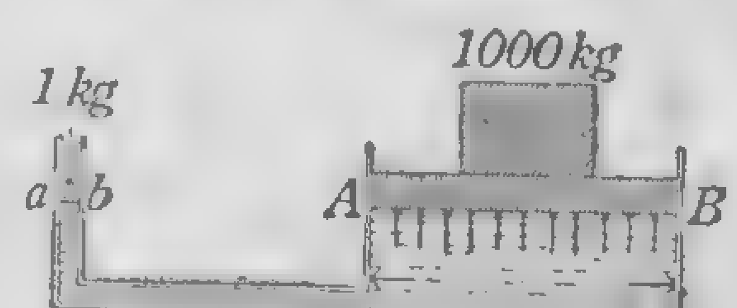


FIG. 14. Multiplication of force by transmission of pressure

24. The hydraulic press. The experimental proof of the correctness of the conclusions of the preceding paragraph is furnished by the hydraulic press, an instrument now in common use for subjecting to enormous pressures paper, cotton, etc. and for punching holes through iron plates, testing the strength of iron beams, extracting oil from seeds, making dies, embossing metal, braking automobiles, etc. Hydraulic presses of great power have been designed for use in steel works to replace huge steam hammers (see opposite page 16). Compressions of 14,000 tons or more are thus obtained. Much cold steel, as well as hot, is now pressed instead of hammered.

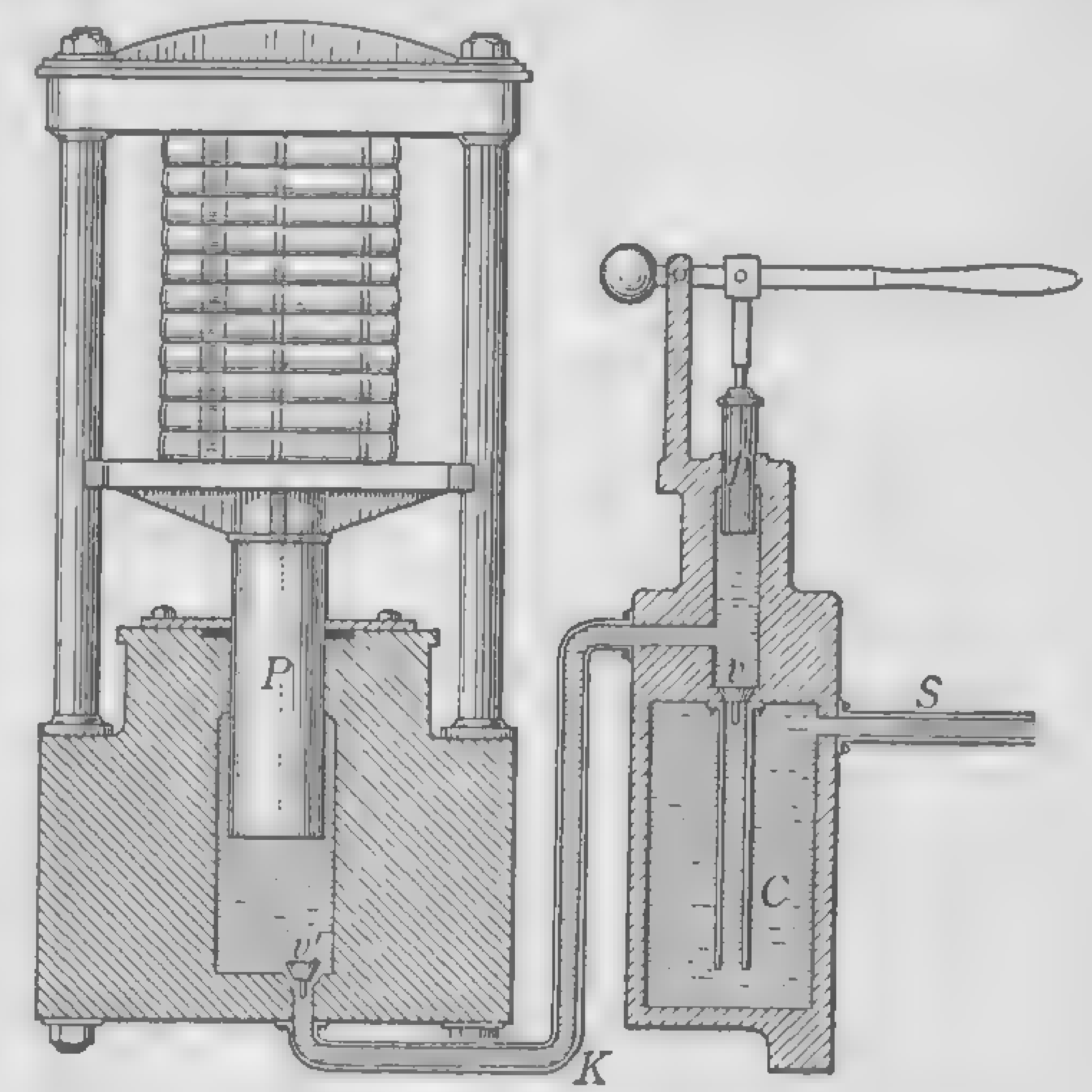


FIG. 15. Diagram of a hydraulic press

When the small piston *p* of the press shown in Fig. 15 is raised, water from the cistern *C* enters the piston chamber through the valve *v*. As soon as the downstroke begins, the valve *v* closes, the valve *v'* opens, and the pressure applied on the piston *p* is transmitted through the tube *K* to the large reservoir, where it acts on the large cylinder *P*.

The force exerted upon P is as many times that applied to p as the area of P is times the area of p.

25. No gain in the product of force times distance. It should be noticed that while the force acting on *AB* (Fig. 14) is 1000 times as great as the force acting on *ab*, the distance through which the piston *AB* is pushed up in a given time is but $\frac{1}{1000}$ of the distance through which the piston *ab* moves down. For forcing *ab* down a distance of 1 centimeter crowds but 1 cubic centimeter of water over into the large cylinder,

and this additional cubic centimeter can raise the level of the water there but $\frac{1}{1000}$ centimeter. We see, therefore, *that the product of the force acting by the distance moved is precisely the same at both ends of the machine.* This important conclusion will be found in our future study to apply to every type of machine.

26. The hydraulic elevator. Another very common use of the above principle of the transformation of pressure by liquids is found in the hydraulic elevator. The simplest form of such an elevator is shown in Fig. 16. The cage A is borne on the top of a long piston P, which runs in a cylindrical pit C equal in depth to the height to which the carriage must ascend. Water enters the pit either directly from the water mains, m, of the city's supply or, if this does not furnish sufficient pressure, from a special reservoir on top of the building. When the elevator boy pulls *up* on the cord cc, the valve v opens so as to make connection from m into C. The elevator then ascends. When cc is pulled *down*, v turns so as to permit the water in C to escape into the sewer. The elevator then descends.

Where speed is required, the motion of the piston is communicated indirectly to the cage by a system of pulleys like that shown

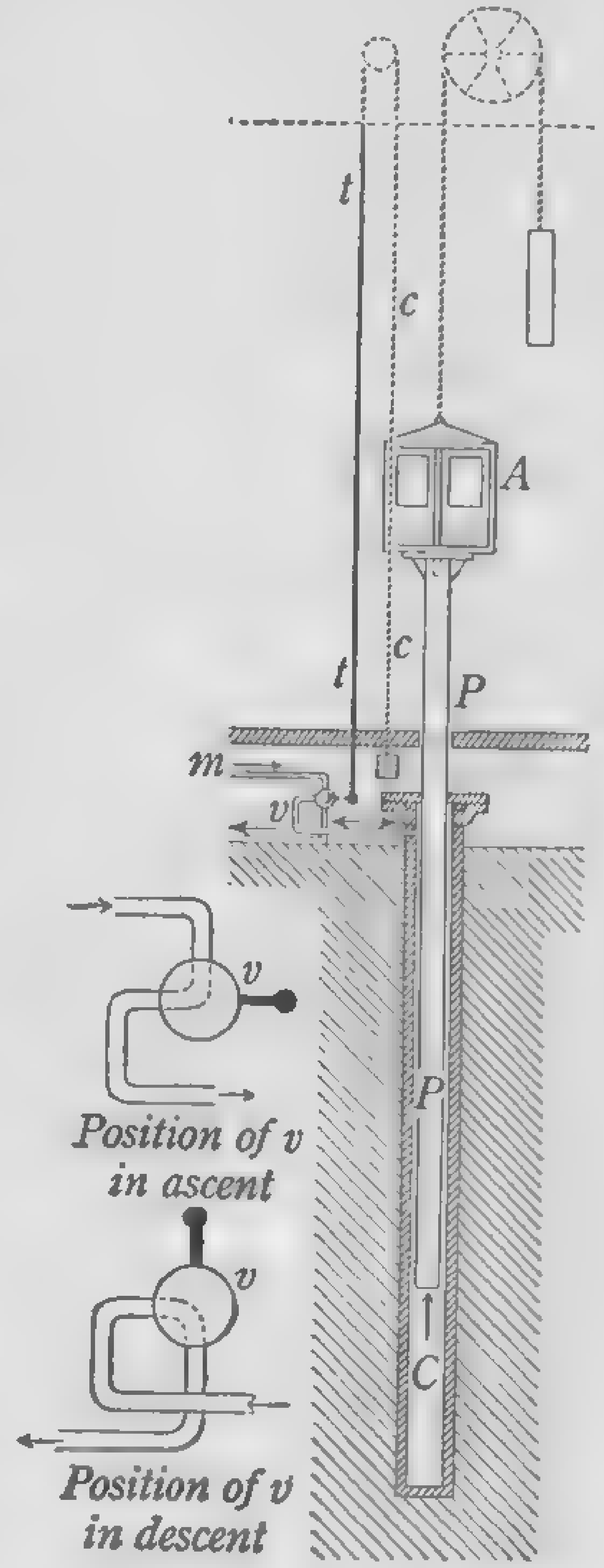


FIG. 16

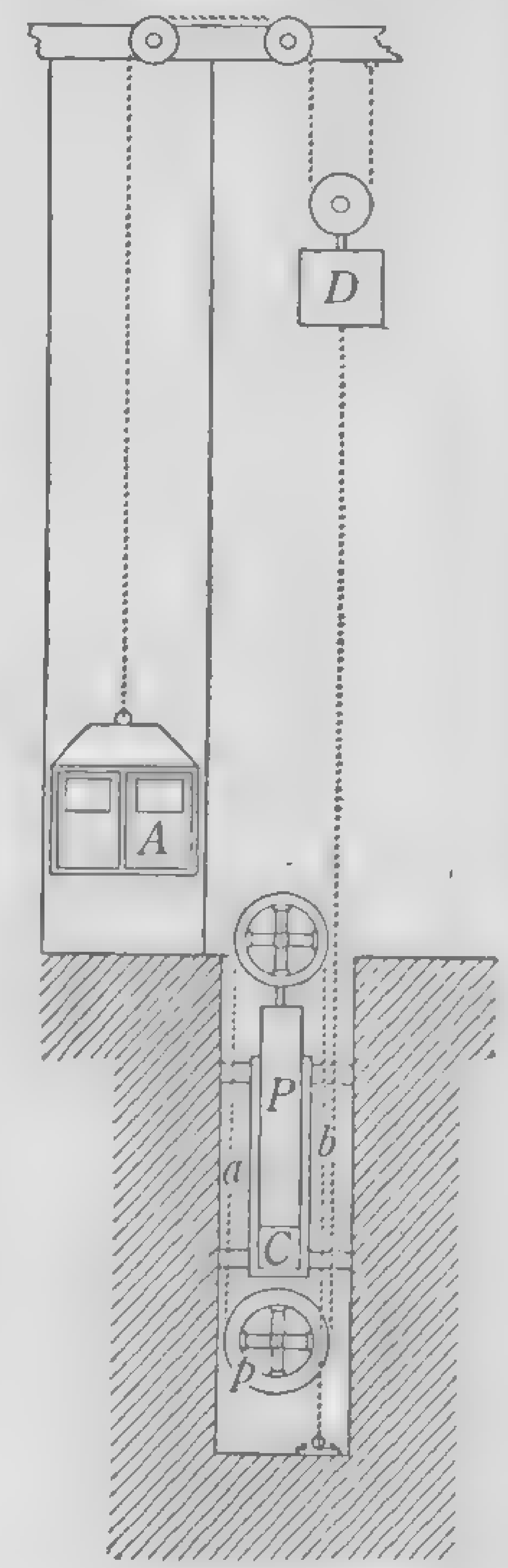
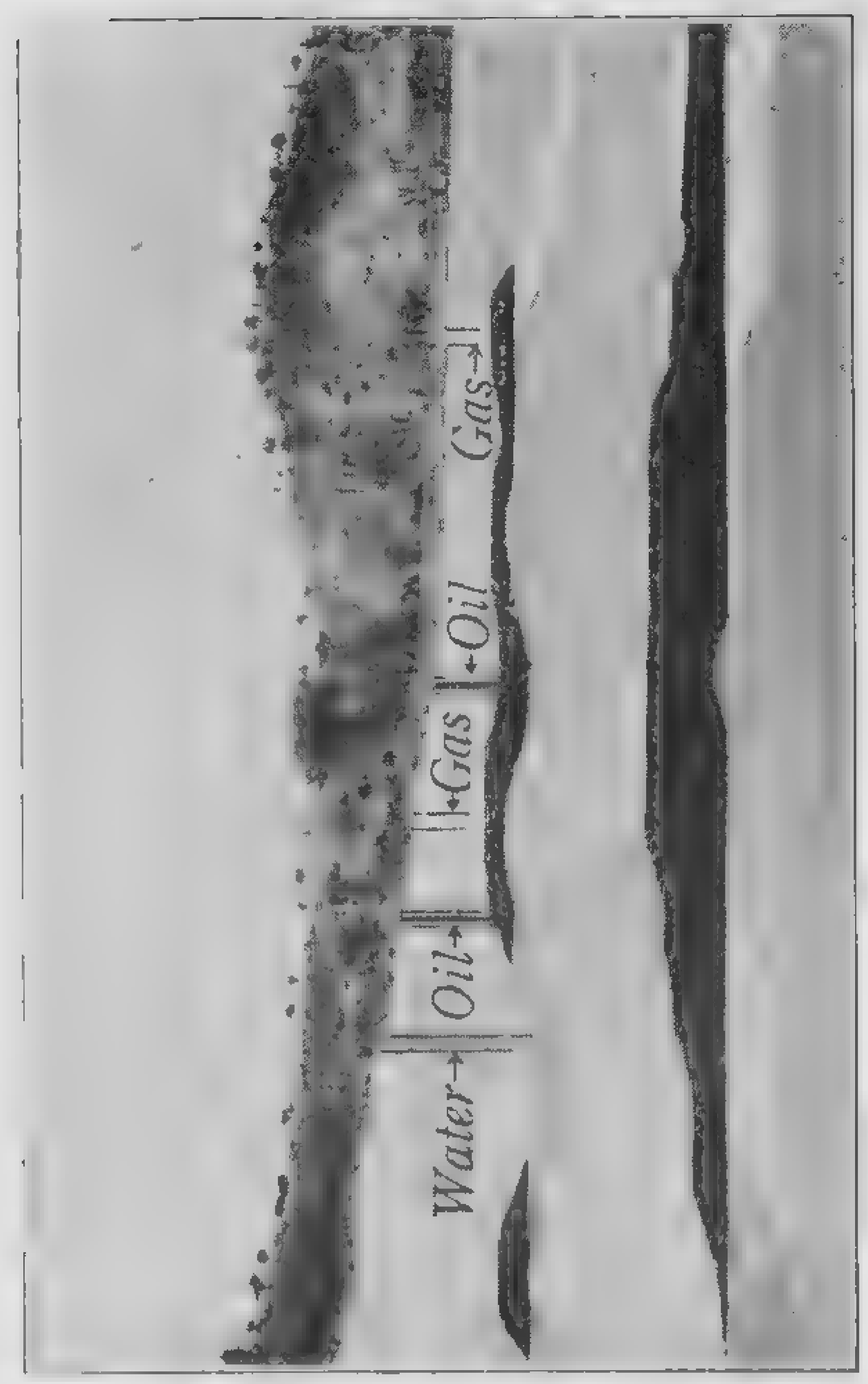


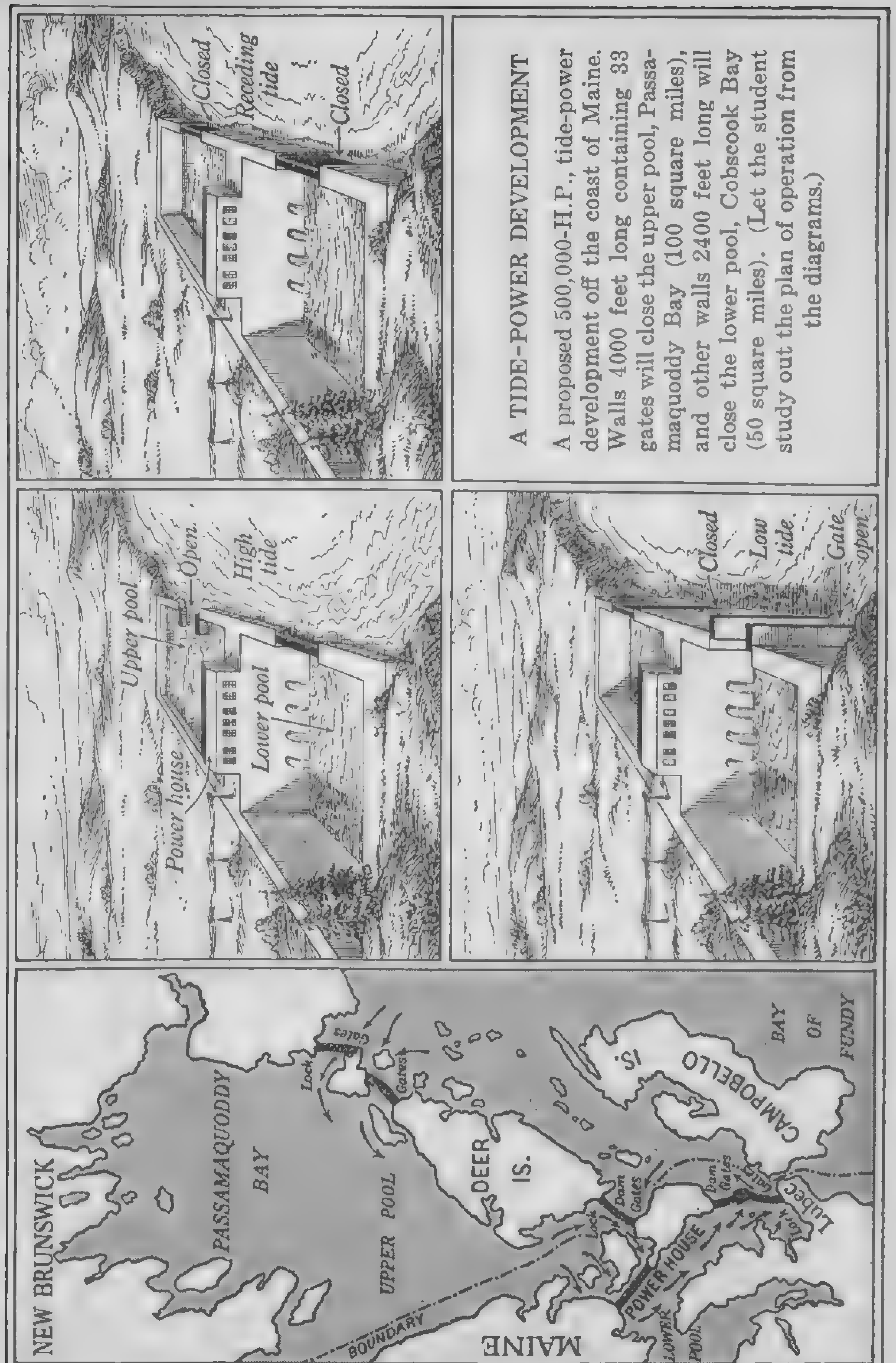
FIG. 17

Diagrams of hydraulic elevators



A SPOUTING OIL WELL

Gas and oil are found in porous rocks having a nonporous covering; for example, the porous rock may be limestone or sandstone, and the nonporous covering may be shale. Frequently water is found below, the oil and the gas being on top. The pressure of the gas sometimes exceeds 1000 pounds to the square inch; hence if a boring is made into the layer of water or oil, the boring tools and derrick may be blown high in the air by the rushing water or oil. When the pressure of the expanding gas falls too low to force the oil from the boring, pumping must be resorted to. Natural gas is sometimes piped for many miles to steel works, where millions of cubic feet of it are burned daily. We have here an illustration of Pascal's law on a grand scale in nature



A TIDE-POWER DEVELOPMENT

A proposed 500,000-H.P., tide-power development off the coast of Maine. Walls 4000 feet long containing 33 gates will close the upper pool, Passamaquoddy Bay (100 square miles), and other walls 2400 feet long will close the lower pool, Cobscook Bay (50 square miles). (Let the student study out the plan of operation from the diagrams.)

in Fig. 17. With this arrangement a foot of upward motion of the piston P causes the counterpoise D of the cage to descend 2 ft.; for it is clear from the figure that when the piston goes up 1 ft., enough rope must be pulled over the fixed pulley p to lengthen each of the two strands a and b 1 ft. Similarly, when the counterpoise descends 2 ft., the cage ascends 4 ft. Hence the cage moves four times as fast and four times as far as the piston. The elevators in the Eiffel Tower in Paris are of this sort. They have a total travel of 420 ft. and are capable of lifting fifty people 400 ft. per minute. The cylinder C and the piston P are often not in a pit, but lie in a horizontal position. (Most modern elevators are electric rather than hydraulic.)

27. City water supply. Fig. 18 illustrates the method by which a city is often supplied with water from a distant

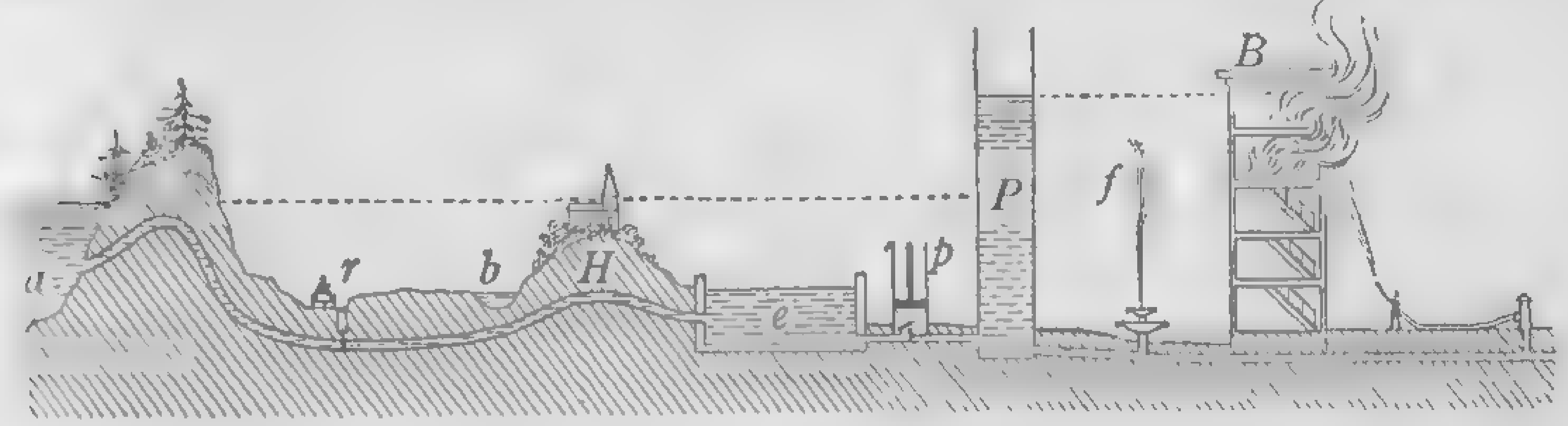


FIG. 18. City water supply from lake

source. The aqueduct from the lake a passes under a road r, a brook b, and a hill H, and into a reservoir e, from which it is forced by the pump p into the standpipe P, whence it is distributed to the houses of the city. If a static condition prevailed in the whole system, then the water level in e would of necessity be the same as that in a, and the level in the pipes of the building B would be the same as that in the standpipe P; but when the water is flowing, the friction of the mains causes the level in e to be somewhat less than that in a, and that in B less than that in P. It is on account of the friction of both the air and the pipes that the fountain f does not rise nearly so high as the ideal limit shown in the figure. When the reservoir e requires cleaning, or in case of accident or need of repairs, the supply of water from the lake a may be partly or wholly cut off by a huge valve, or gate, at r.

SUMMARY. *Pascal's law.* Pressure applied anywhere to a body of confined liquid is transmitted undiminished to every portion of the surface of the containing vessel.

Hydraulic-press rule. The force exerted upon the large piston is as many times that applied to the small piston as the area of the large piston is times that of the small piston. Expressed as a formula,

$$\frac{F}{f}=\frac{A}{a}=\frac{D^2}{d^2}.$$

QUESTIONS AND PROBLEMS

1. A jug full of water may often be burst by striking a blow on the cork. If the interior surface of the jug is 200 sq. in. and the cross section of the cork 1 sq. in., what total force acts on the interior of the jug when a 10-pound blow is struck on the cork?

2. Fig. 19 represents an instrument commonly known as the hydrostatic bellows. If the base C is 50 cm. square and the tube is filled with water to a depth of 1.5 m. above the top of C, what is the value of the weight in kilograms which the bellows can support?

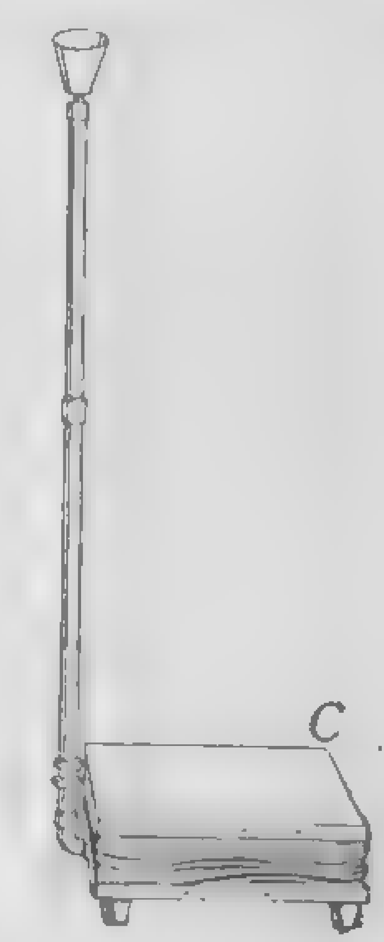


FIG. 19. Hydrostatic bellows

3. The cross-sectional areas of the pistons of a hydraulic press were 3 sq. in. and 60 sq. in. How great a weight would the large piston sustain if 75 lb. were applied to the small one?

4. The diameters of the pistons of a hydraulic press were 2 in. and 20 in. What force would be produced upon the large piston by 50 lb. on the small one?

5. The water pressure in the city mains is 80 lb. to the square inch. The diameter of the piston of a hydraulic elevator of the type shown in Fig. 16 is 10 in. If friction could be disregarded, how heavy a load could the elevator lift? If 30 per cent of the ideal value must be allowed for frictional loss, what load will the elevator lift?

6. How does your city get its water? How is the pressure in the pipes maintained?

THE PRINCIPLE OF ARCHIMEDES*

28. **Buoyant effect of a liquid.** The preceding experiments have shown that an upward force acts against the bottom of any body immersed in a liquid. If the body is a boat, a cork, a piece of wood, or any body which floats, it is clear that since it is in equilibrium this upward force must be equal to the weight of the body. Even if the body does not float, everyday observation shows that it still loses a portion of its natural weight; for it is well known that it is easier to lift a stone under water than in air, or, again, that a man in a bath-tub can support his whole weight by pressing lightly against the bottom with his fingers. It was, indeed, this very observation which first led the old Greek philosopher Archimedes (287–212 B.C.) to the discovery of the exact law which governs the buoyant effect of a liquid upon a body placed in it.

Hiero, the tyrant of Syracuse, had ordered a gold crown made, but suspected that the artisan had fraudulently used silver as well as gold in its construction. He ordered Archimedes to discover whether or not this was true. How to do so without destroying the crown was at first a puzzle to the old philosopher. While in his daily bath, noticing the loss of weight of his own body, it suddenly occurred to him that *any body immersed in a liquid apparently loses a weight equal to the weight of the displaced liquid.* He is said to have jumped at once to his feet and rushed through the streets of Syracuse crying "Eureka! Eureka!" (I have found it! I have found it!).

29. **Theoretical proof of Archimedes' principle.** It is probable that Archimedes, with that faculty which is so common among men of great genius, saw the truth of his conclusion without going through any logical process of proof. Such a proof, however, can easily be given. Thus, the upward force F on the bottom of the block B (Fig. 20) is equal to the

* A laboratory exercise on the experimental proof of Archimedes' principle should either precede or accompany this discussion. See, for example, Experiment 5 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

weight of the column of liquid C. The downward force F' on the top of this block is equal to the weight of the column of liquid C'. It is, then, clear that the upward force must exceed the downward force by the weight of the liquid whose volume is equal to that of the block. Archimedes' principle may be stated thus:

The buoyant force exerted by a liquid is exactly equal to the weight of the displaced liquid.

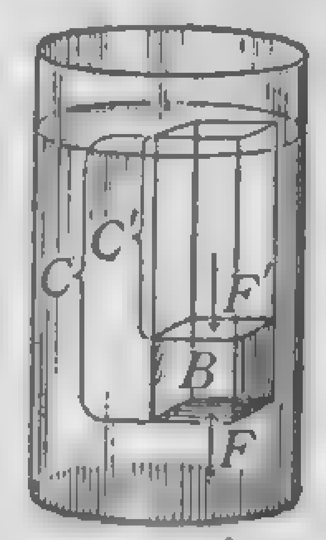


FIG. 20. Proof that an immersed body is buoyed up by a force equal to the weight of the displaced liquid

The reasoning is exactly the same, no matter what may be the nature of the liquid in which the body is immersed, nor how far the body may be beneath the surface. Further, if the body weighs more than the liquid which it displaces, it must sink; for it is urged down with the force of its own weight, and up with the lesser force of the weight of the displaced liquid. But if it weighs less than the displaced liquid, then the upward force due to the displaced liquid is greater than its own weight, and consequently it must rise to the surface. When it reaches the surface, the downward force upon the top of the block, due to the liquid, becomes zero. The body must, however, continue to rise until the upward force on its bottom is equal to its own weight. But this upward force is always equal to the weight of the displaced liquid; that is, to the weight of the column of liquid *mbcn* (Fig. 21). Hence

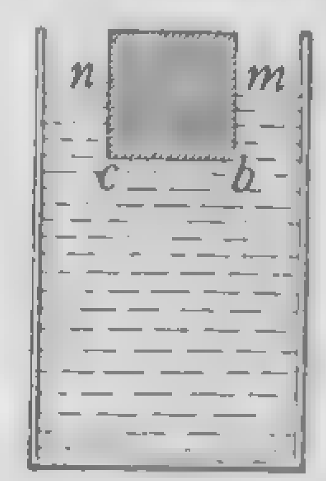
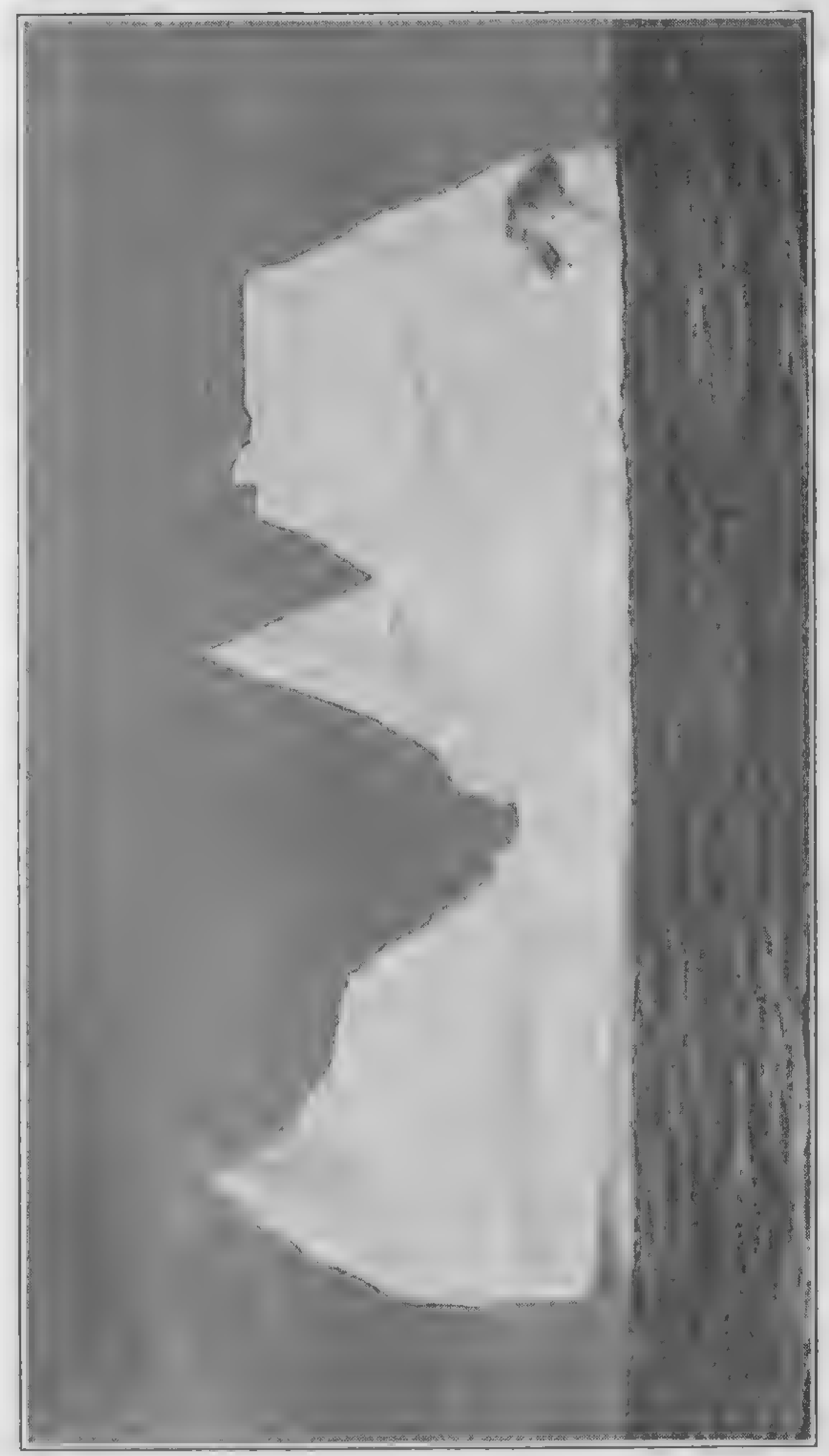


FIG. 21. Proof that a floating body is buoyed up by a force equal to the weight of the displaced liquid

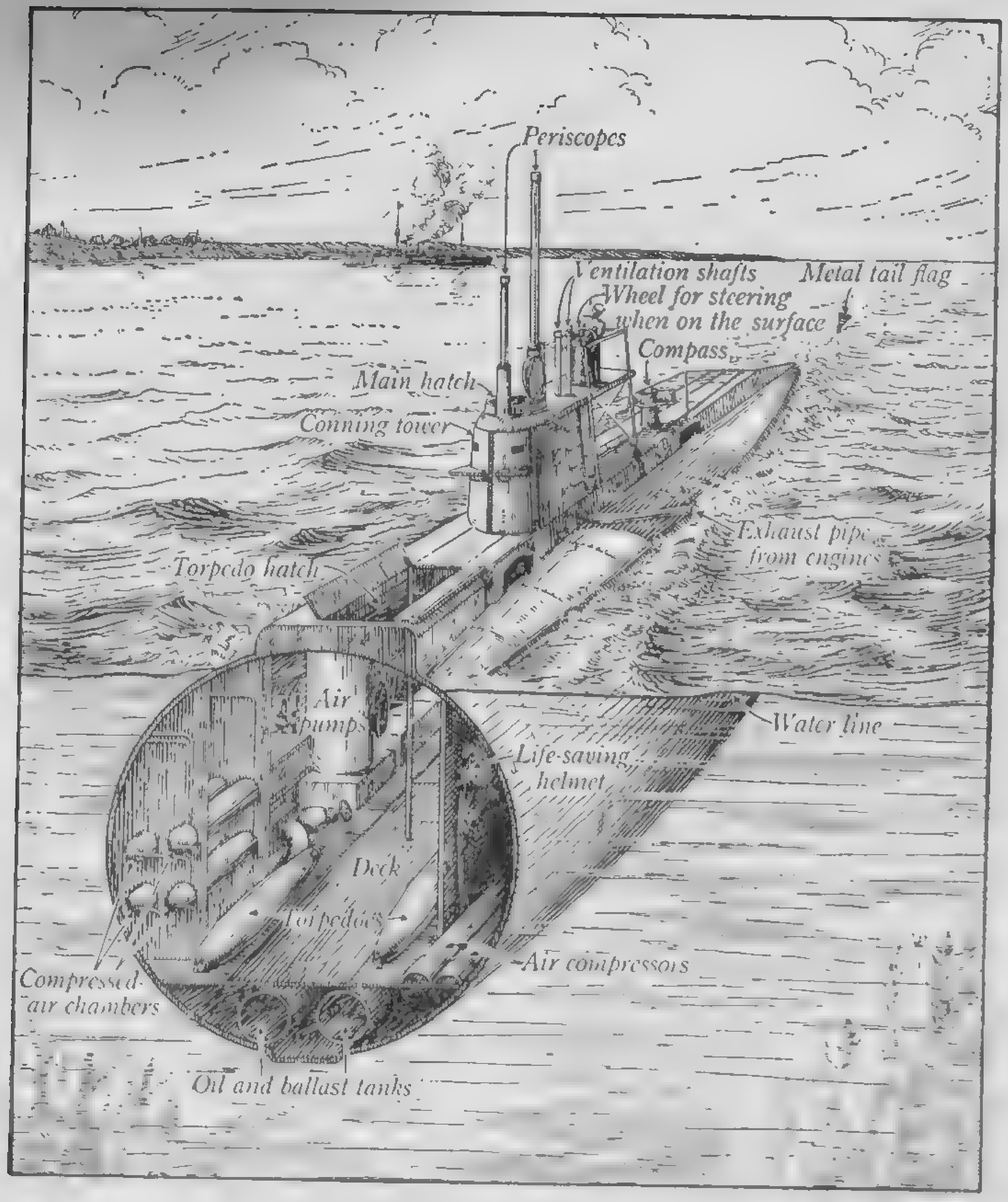
A floating body displaces its own weight of the liquid in which it floats.

This statement is embraced in the statement of Archimedes' principle, for a body which floats has lost its whole weight (see opposite page).



AN ICEBERG

This huge iceberg was formed by the movement into the sea of the great glacial ice cap of Greenland. Glacier ice being somewhat porous has a density less than that of solid ice. About six sevenths of the mass of an iceberg is below the level of the sea, the bottom in some cases being at least 1500 feet below the surface. Some icebergs contain enough ice to cover a square mile to a depth of 500 feet



THE DETAILS OF A SUBMARINE

The submarine, one of the newest of marine inventions, is a simple application of the principle of Archimedes, — one of the oldest principles of physics. In order to submerge, the submarine allows water to enter her ballast tanks until the total weight of the boat and contents becomes nearly as great as that of the water she is able to displace. The boat is then almost submerged. When she is under headway in this condition, a proper use of the horizontal, or diving, rudders sends her beneath the surface, or, if submerged, brings her to the surface, so that she can scan the horizon with her periscope. The whole operation takes but a few seconds. When the submarine wishes to come to the surface for recharging her batteries or for other purposes, she blows compressed air into her ballast tanks, thus driving the water out of them. Submarines are propelled on the surface by Diesel oil engines; underneath the surface, by storage batteries and electric motors

To test our reasoning for this case, place an overflow can (Fig. 22) on a trip scale, fill it with water, and carefully balance it. Now float a block of wood in the can. When the overflow of water ceases, the scales again balance. What do you conclude?

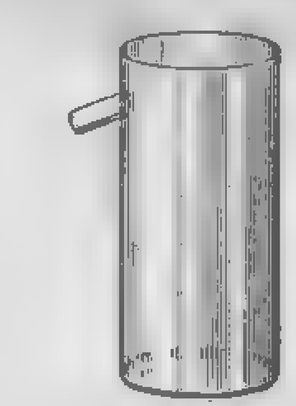


FIG. 22. An overflow can

30. Specific gravity of a heavy solid. The specific gravity of a body is by definition the ratio of its weight to the weight of an equal volume of water (§ 16). Since a submerged body displaces a volume of water equal to its own volume, however irregular it may be,

$$\text{Specific gravity of body} = \frac{\text{weight of body}}{\text{weight of water displaced}}.$$

Making application of Archimedes' principle, we have

$$\text{Specific gravity of body} = \frac{\text{weight of body}}{\text{buoyancy (or loss of weight in water)}}.$$

31. Specific gravity of a solid lighter than water. If the body is too light to sink of itself, we may still obtain the weight of the equal volume of water by forcing it beneath the surface by means of a sinker. Thus, suppose w_1 represents the weight on the right pan of the balance when the body is in air and the sinker is under water, as in Fig. 23, and w_2 the weight on the right pan when both body and sinker are under water. Then $w_1 - w_2$ is obviously the buoyant effect of the water upon the body alone (or its loss of weight in water) and is therefore equal to the weight of the displaced water.

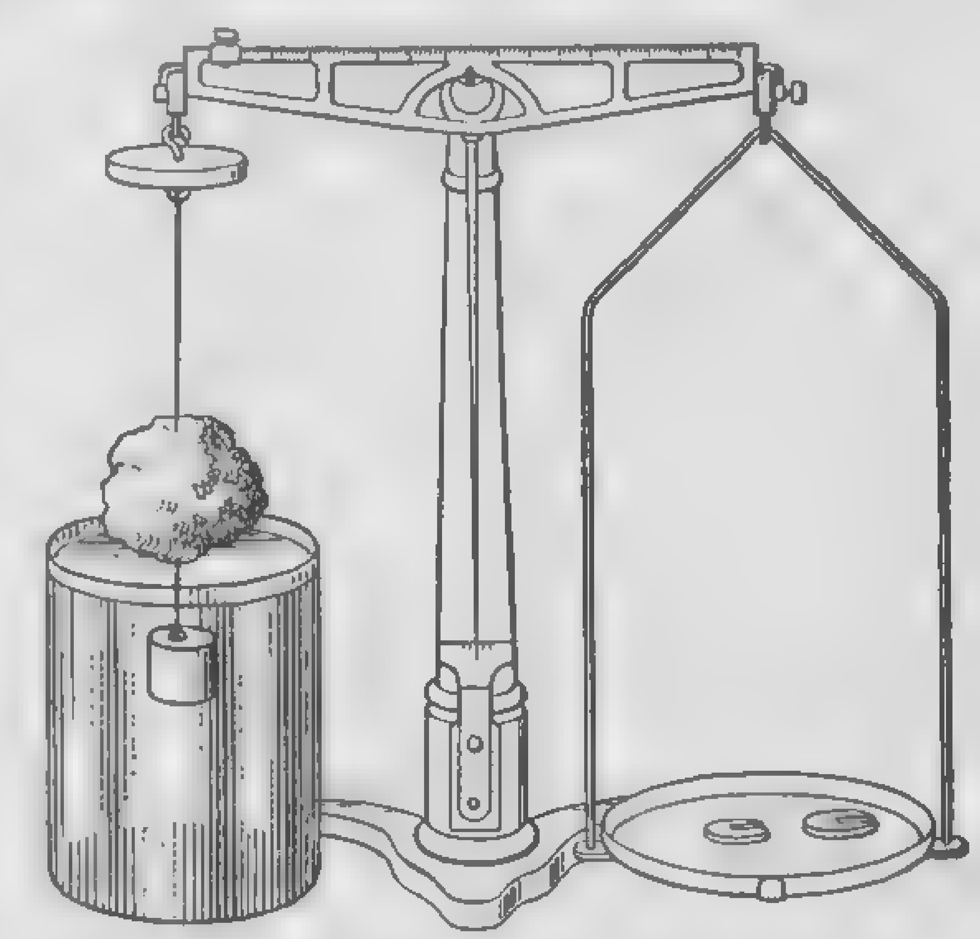


FIG. 23. Method of finding specific gravity of a light solid

32. Specific gravity of liquids by the hydrometer method. The hydrometer was invented by the Greeks about sixteen hundred years ago. The commercial hydrometer that is now commonly used for testing the specific gravity of alcohol, milk, acids, sugar solutions, etc. is of the form shown in Fig. 24. The stem is calibrated by trial so that the specific gravity of any liquid may be read upon it directly. The principle involved is that a floating body sinks until it has displaced its own weight. By making the stem very slender the sensitiveness of the instrument may be made very great. Why? (See p. 305.)

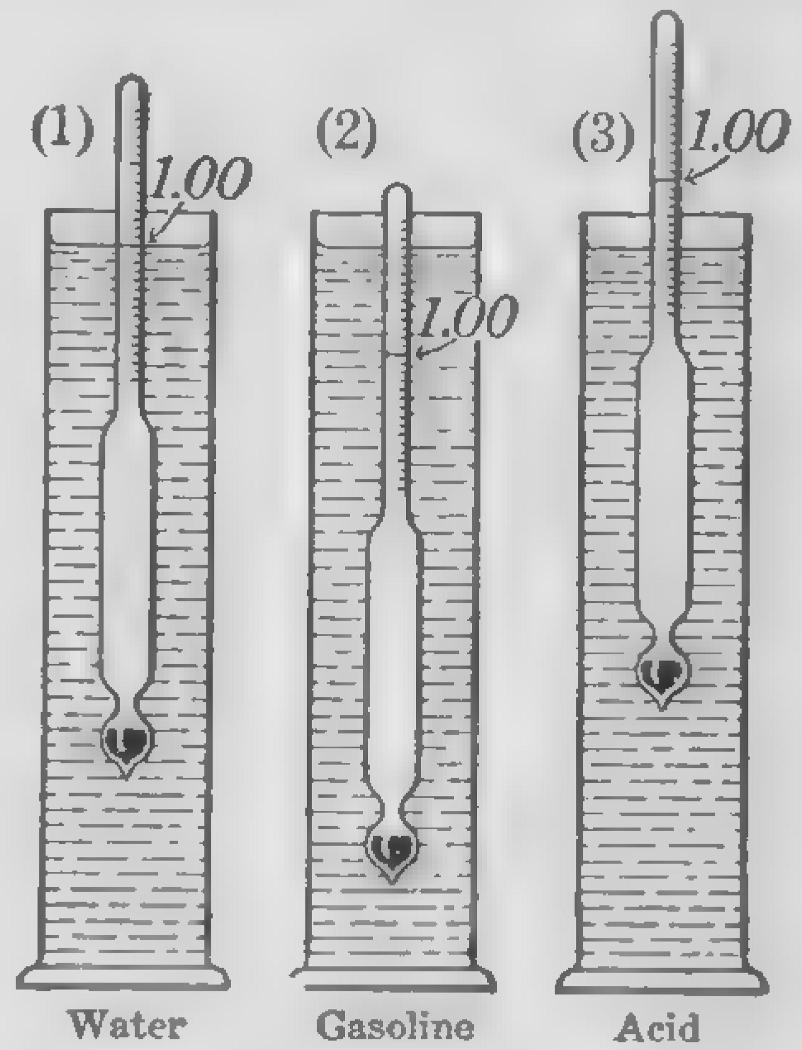


FIG. 24. Constant-weight hydrometer

33. Specific gravity of liquids by "loss of weight" method. If any suitable solid be weighed first in air, then in water, and then in a liquid of unknown specific gravity, by the principle of Archimedes its loss of weight in the liquid is equal to the weight of the liquid displaced, and its loss in water is equal to the weight of the water displaced. If we divide the loss of weight in the liquid by the loss of weight in water, we are dividing the weight of a given volume of liquid by the weight of an equal volume of water. Therefore,

*To find the specific gravity of a liquid, divide the loss of weight of some solid in it by the loss of weight of the same body in water.**

SUMMARY. *Archimedes' principle.* **The buoyant force exerted by a liquid is equal to the weight of the displaced liquid.**

$$\text{Specific gravity of a heavy solid} = \frac{\text{weight of solid}}{\text{loss of weight in water}}.$$

* Laboratory experiments on the determination of the densities of solids and liquids should follow or accompany the discussion of this chapter. See, for example, Experiments 6 and 7 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

Specific gravity of light solid (sinker method)

$$= \frac{\text{weight of solid}}{(\text{weight of solid in air} + \text{sinker in water}) - \text{weight of both in water}}.$$

Specific gravity of a liquid ("loss of weight," or "bulb," method)

$$= \frac{\text{loss of weight of solid in liquid}}{\text{loss of weight of solid in water}}.$$

QUESTIONS AND PROBLEMS *

1. Explain by reference to the upward and downward forces of water and the weight of the body (1) why a piece of cork when released under water rises; (2) why a piece of iron or stone sinks.

2. Does the weight apparently lost by a submerged body depend upon its volume or its weight? Explain.

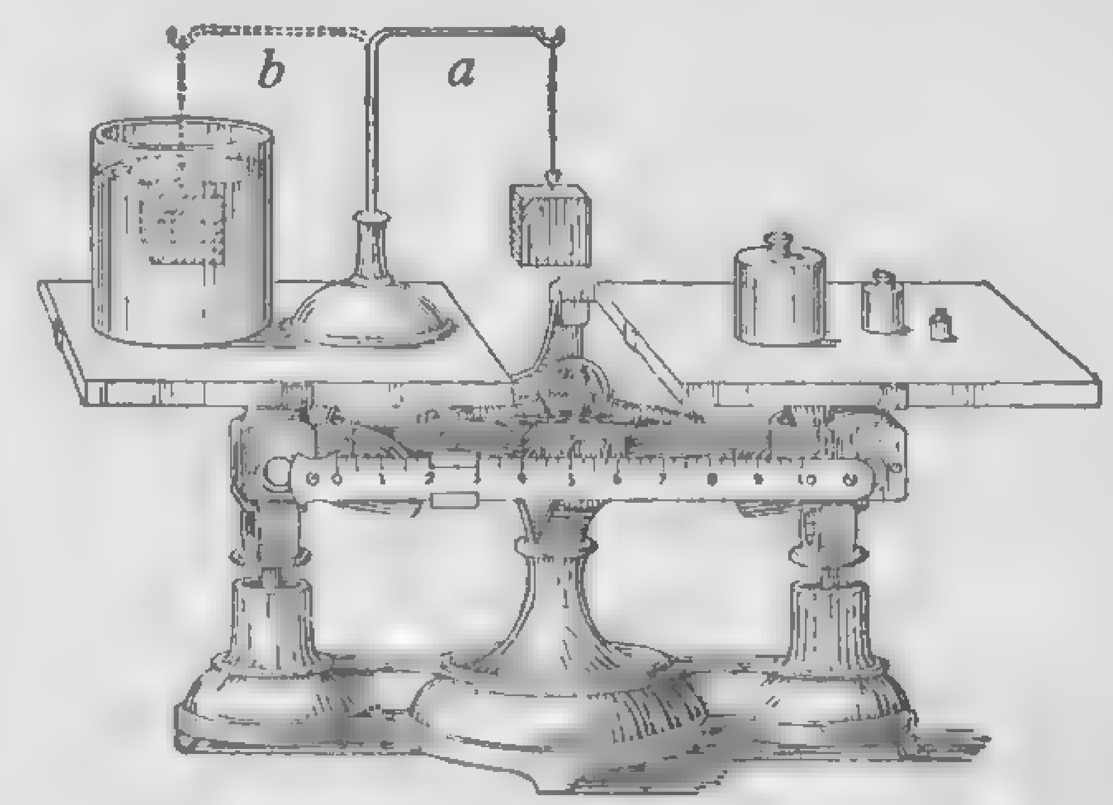


FIG. 25

3. A piece of lead on one side of a trip scale balances a piece of aluminum on the other side. If the trip scale is now immersed in a tub of water, which metal will appear to be the heavier? Explain clearly.

4. Let a vessel of water, together with an object heavier than water, be counterpoised as in Fig. 25 (position a). Now if the object be placed inside the vessel of water (position b), will the scales remain balanced? Predict the result, and then try the experiment.

5. A brick lost 1 lb. when submerged 1 ft. deep. How much would it lose if suspended 3 ft. deep?

6. Steel is three times as dense as aluminum. When equal volumes of the two are submerged in water, how do their apparent losses of weight compare?

7. A boy who can just float weighs 124.8 lb. What is his volume?

* Supplementary questions and problems for Chapter II are given in the Appendix.

8. An empty milk bottle weighed 1 lb. $10\frac{1}{2}$ oz.; filled with water, it weighed 3 lb. $11\frac{1}{2}$ oz.; filled with milk, it weighed 3 lb. $12\frac{1}{2}$ oz. Find the specific gravity of this specimen of milk.

9. A graduated glass cylinder contains 190 cc. of water. An egg weighing 40 g. is dropped into the glass; it sinks to the bottom and raises the water to the 225-cubic-centimeter mark. Find the density of the egg.

10. A body loses 25 g. in water, 23 g. in oil, and 20 g. in alcohol. Find the specific gravity of the oil and of the alcohol.

11. A platinum ball weighs 330 g. in air, 315 g. in water, and 303 g. in sulphuric acid. Find the volume of the ball and the specific gravity of the platinum and of the acid.

12. A cubic foot of stone weighed 110 lb. in water. Find (1) its density in pounds per cubic foot; (2) its specific gravity.

13. A piece of sandstone having a specific gravity of 2.6 weighs 480 g. in water. Find its weight in air.

14. A cube of iron 10 cm. on a side weighs 7500 g. What will it weigh in alcohol of density .82 g. per cubic centimeter?

15. The hull of a modern battleship is made almost entirely of steel, its walls being of steel plates from 6 to 18 in. thick. Explain how it can float.

16. Will a boat rise or sink deeper in the water as it passes from a river to the ocean?

17. Do the larger numbers appear on hydrometers toward the bottom of the stem or toward the top? Explain.

18. A barge 30 ft. by 15 ft. sank 4 in. when an elephant was taken aboard. What was the elephant's weight?

19. What fraction of the volume of a block of wood will float above water if its specific gravity is .5? if its specific gravity is .6? if its specific gravity is .9? State in general what fraction of the volume of a floating body is under water.

20. A block of wood 10 in. high sinks 6 in. in water. Find the specific gravity of the wood.

21. What must be the specific gravity of a liquid in which a body having a specific gravity of 6.8 will float with half its volume submerged?

22. A piece of paraffin weighed 178 g. in air, and a sinker weighed 30 g. in water. Both together weighed 8 g. in water. Find the specific gravity of the paraffin.

23. If in Problem 22 half the paraffin be cut away, the weight of the remainder in water, with the sinker attached, is 19 g. instead of 8 g. Prove that this is true and explain the apparent increase in weight.

24. Suppose Hiero's crown weighed 1070 g. and lost 60 g. weight in water. Find (1) how many cubic centimeters of gold there were in the crown; (2) how many cubic centimeters of silver; (3) how many grams of gold; (4) how many grams of silver. (See table of densities, p. 8.)

CHAPTER III

PRESSURE IN AIR

BAROMETRIC PHENOMENA

34. The weight of air. To ordinary observation air is barely perceptible. It appears to have no weight and to offer no resistance to bodies which pass through it. If, however, a bulb is balanced as in Fig. 26, and then removed and filled with air under pressure by a few strokes of a bicycle pump, it will be found, when placed on the balance again, to be heavier than it was before. On the other hand, if the bulb is connected with an air pump and exhausted, it will be found to have lost weight.* Evidently, then, air can be put into and taken out of a vessel, weighed, and handled, just like a liquid or a solid.

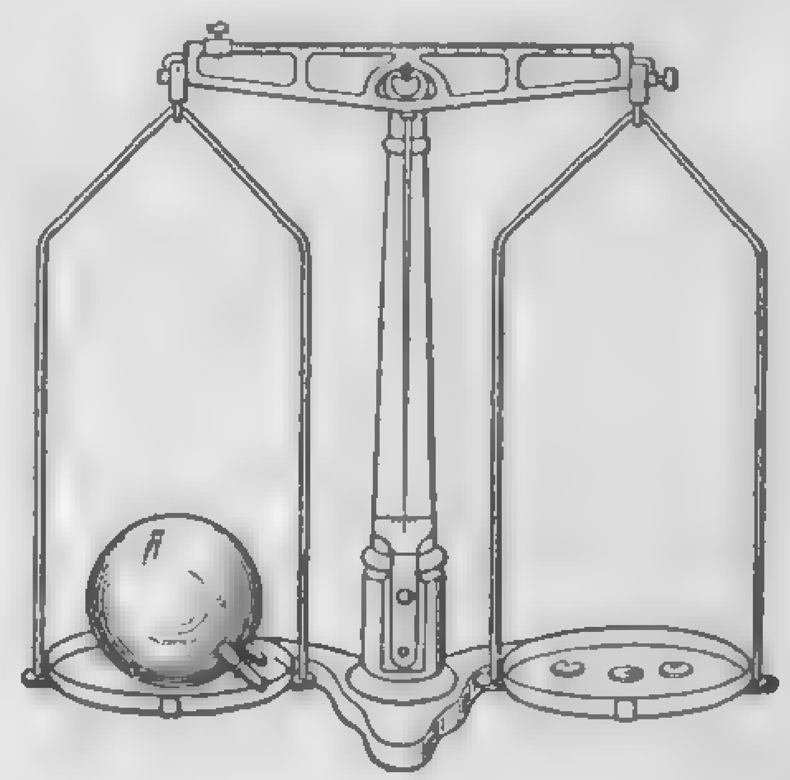


FIG. 26. Proof that air has weight

We are accustomed to say that bodies are "as light as air"; yet careful measurement shows that it takes but 12 cubic feet of air to weigh a pound. Therefore a single large room contains more air than an ordinary man can lift. Thus, the air in a room 60 feet by 30 feet by 15 feet weighs more than a ton. The exact density of air at the freezing temperature and under normal atmospheric pressure is .001293 gram per cubic centimeter. A given volume of air therefore weighs $\frac{1}{773}$ as much as an equal volume of water.

* Another experiment is to weigh an electric-light bulb, and then puncture it with a blowpipe and weigh it again.

35. Proof that air exerts pressure. Since air has weight, it is to be inferred that air, like a liquid, exerts force against any surface immersed in it. The following experiments prove this.

Let a rubber membrane be stretched over a glass vessel, as in Fig. 27. As the air is exhausted from beneath the membrane the latter will be observed to be more and more depressed until it will finally burst under the pressure of the air above.

Again, partly fill a tin can with water and boil the water. The air will be expelled by the escaping steam. While the boiling is still going on, let the can be tightly corked, and then be placed in a sink or a tray and cold water poured over it. The steam will be condensed, and the weight of the air outside will crush the can (see Fig. 28).

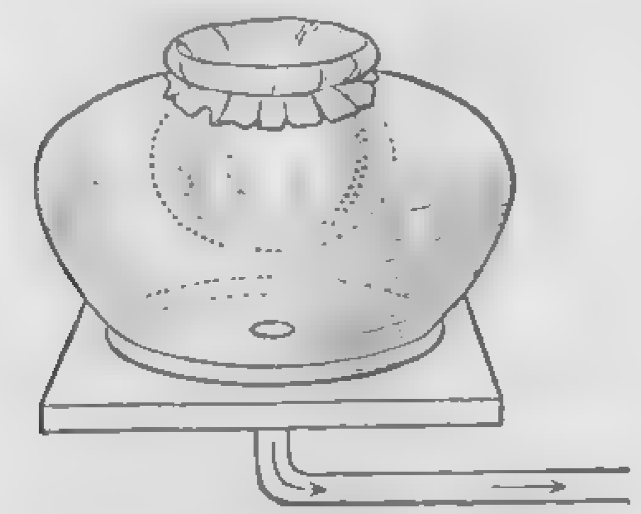


FIG. 27. Rubber membrane stretched by the weight of air

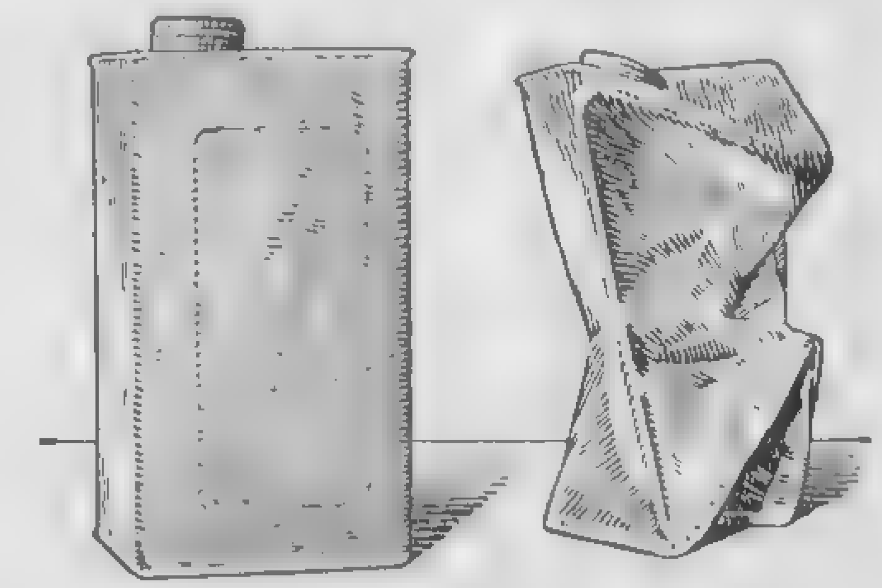


FIG. 28. Gallon can crushed by atmospheric pressure

36. Cause of the rise of liquids in exhausted tubes. If the lower end of a long tube is dipped into water and the air exhausted from the upper end, water will rise in the tube. We prove the truth of this statement every time we draw lemonade through a straw. The old Greeks and Romans explained such phenomena by saying that "nature abhors a vacuum," and this explanation was still in vogue in Galileo's time. But in 1640 the duke of Tuscany had a deep well dug near Florence, and found to his surprise that no water pump that could be obtained would raise the water higher than about 32 feet above the level in the well. When he applied to the aged Galileo (see page 80) for an explanation, the latter replied that evidently "nature's abhorrence of a vacuum

does not extend beyond 32 feet." It is quite probable that Galileo suspected that the pressure of the air was responsible for the phenomenon, for he had himself already proved that air has weight; and, furthermore, he at once devised another experiment to test, as he said, the "power of a vacuum." He died in 1642, before the experiment was performed, but he had suggested to his pupil Torricelli that he continue the investigation.

37. Torricelli's experiment. Torricelli argued that if water would rise 32 feet, then mercury, which is about 13 times as heavy as water, ought to rise but $\frac{1}{13}$ as high. To test this inference he performed in 1643 this famous experiment:

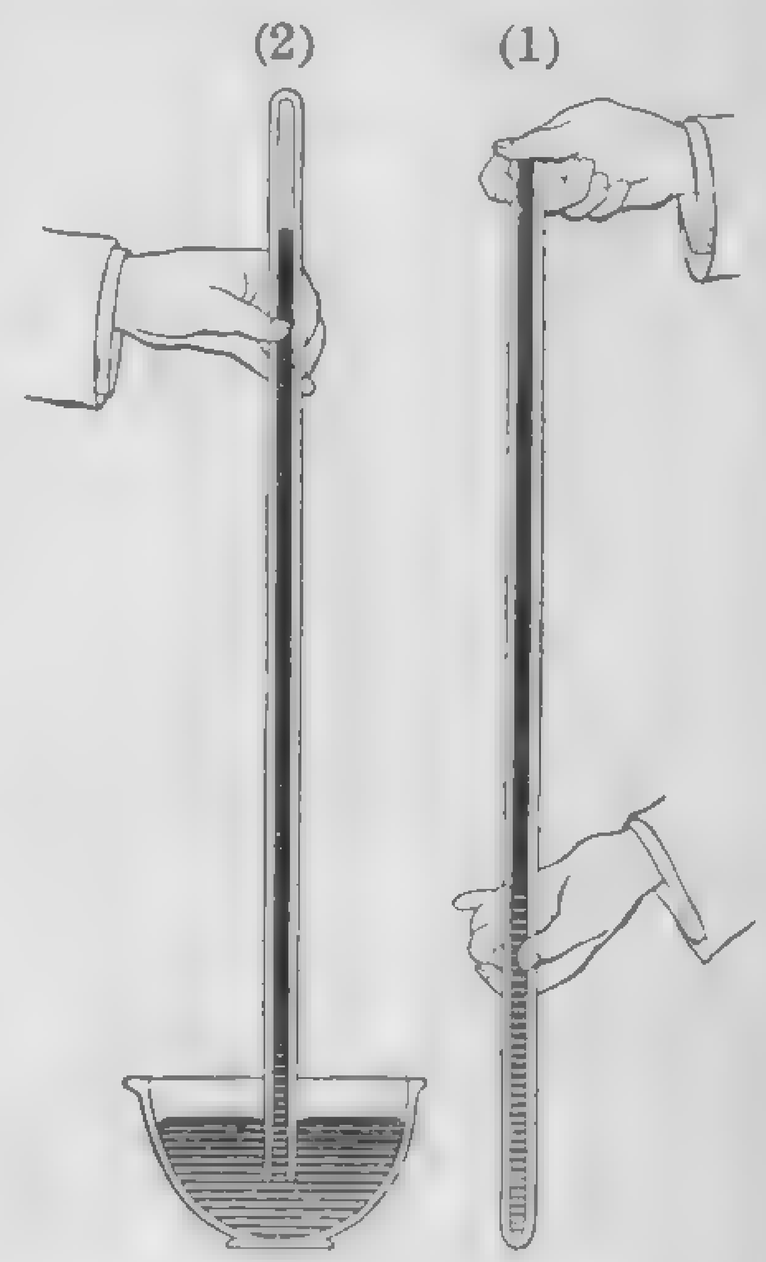


FIG. 29. Torricelli's experiment

Let a tube about 4 ft. long, sealed at one end, be completely filled with mercury, as in Fig. 29 (1), closed with the thumb, and inverted; then let the bottom be immersed in a dish of mercury, as in Fig. 29 (2). When the thumb is removed from the bottom of the tube, the mercury will fall away from the upper end of the tube, in spite of the fact that in so doing it will leave a vacuum above it; and its upper surface will, in fact, stand about $\frac{1}{13}$ of 32 ft. (that is, between 29 and 30 in.) above the mercury in the dish.

Torricelli concluded from this experiment that the rise of liquids in exhausted tubes is due to an outside pressure exerted by the atmosphere on the surface of the liquid, and not to any mysterious sucking power created by the vacuum, as is popularly believed even today.

38. Further decisive tests. An unanswerable argument in favor of this conclusion will be furnished if the mercury in the tube falls as soon as the air is removed from above the surface of the mercury in the dish.

To test this point let the dish and the tube be placed on the table of an air pump, as in Fig. 30, the tube passing through a tightly fitting rubber stopper A in the bell jar. As soon as the pump is started, the mercury in the tube will, in fact, be seen to fall. As the pumping is continued, it will fall nearer and nearer to the level in the dish, although it will not usually reach it, for the reason that an ordinary air pump is not capable of producing so low a pressure as that which exists in the top of the tube. As the air is allowed to return to the bell jar, the mercury will rise in the tube to its former level.

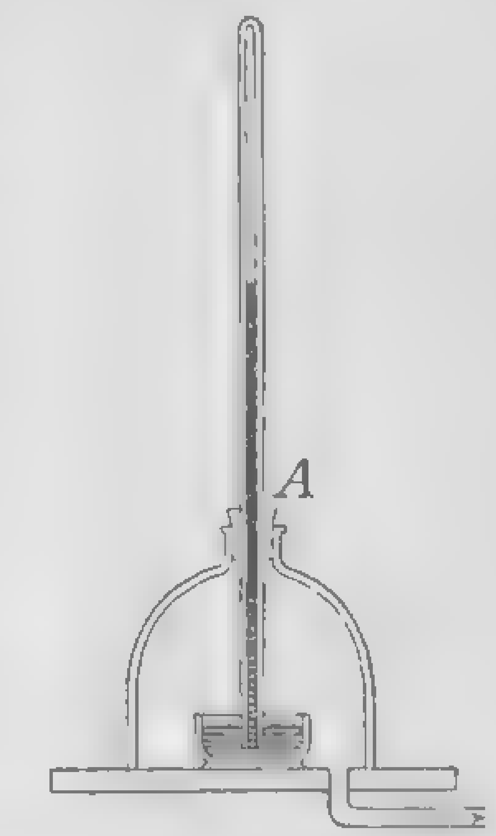


FIG. 30. Barometer falls when air pressure on the mercury surface is reduced

39. Amount of the atmospheric pressure. Torricelli's experiment shows exactly how great the atmospheric pressure is, since this pressure is able to balance a column of mercury of definite length. As the pressures along the same level ac (Fig. 31) are equal, the downward pressure exerted by the atmosphere on the surface of the mercury at c is equal to the downward pressure of the column of mercury at a. But the downward pressure at this point within the tube is equal to hd, where d is the density of the mercury and h is the depth below the surface b. Since the average height of this column at sea level is found to be 76 centimeters (about 30 inches), and since the density of mercury is 13.6 grams per cubic centimeter, the downward pressure inside the tube at a is equal to 76 times 13.6 grams, or 1033.6 grams per square centimeter. Therefore the atmospheric pressure acting on the surface of the mercury at c is 1033.6 grams, or approximately 1 kilogram per square centimeter. In English units

$$\begin{aligned} hd &= \frac{30}{12} \times 62.4 \times 13.6 \\ &= 2121.6 \text{ lb. per square foot} \\ &= 14.7 \text{ lb. per square inch.} \end{aligned}$$

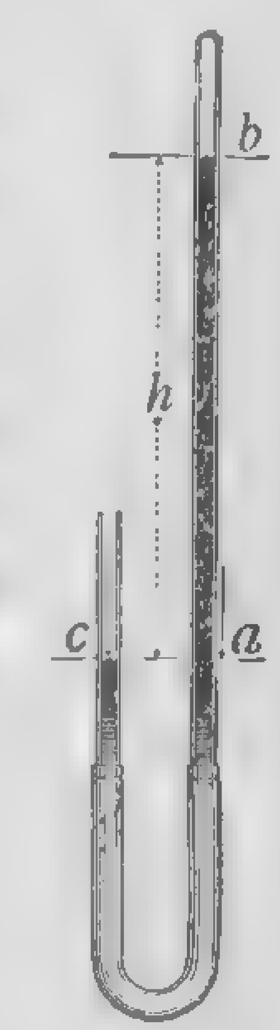


FIG. 31

The pressure of one atmosphere is, then, about 15 pounds per square inch, or about 1 ton per square foot.

40. Pascal's experiment. Pascal thought of another way of testing whether or not it is indeed the weight of the outside air which sustains the column of mercury in an exhausted tube. He reasoned that since the pressure in a liquid diminishes on ascending toward the surface, atmospheric pressure ought also to diminish as one passes from sea level to a mountain top. As there was no mountain near Paris, he carried Torricelli's apparatus to the top of a high tower and found, indeed, a slight fall in the height of the column of mercury. He then wrote to his brother-in-law, Perrier, who lived near Puy-de-Dôme, a mountain in southern France, and requested him to perform the experiment on a larger scale. Perrier wrote back that he was "ravished with admiration and astonishment" when he observed that on ascending 1000 meters (or $\frac{5}{8}$ of a mile) the mercury sank about 8 centimeters (or about 3 inches) in the tube. This was in 1648, five years after Torricelli's discovery.

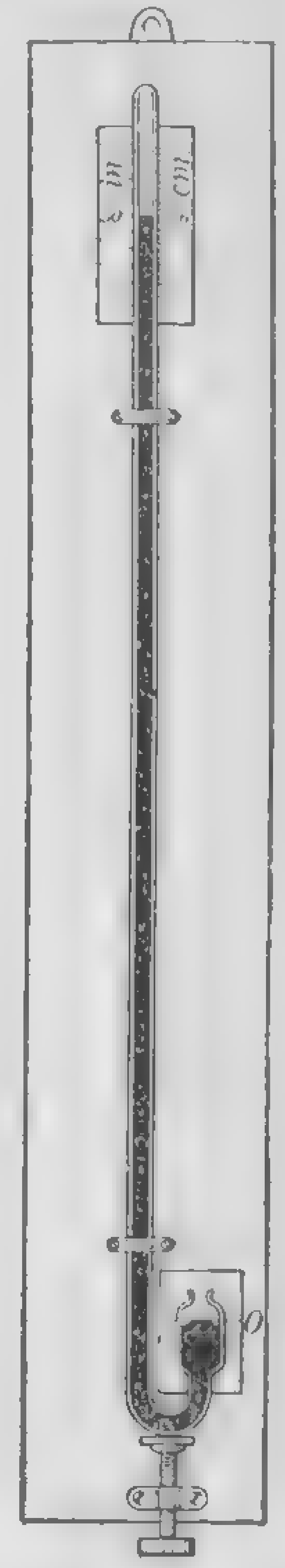


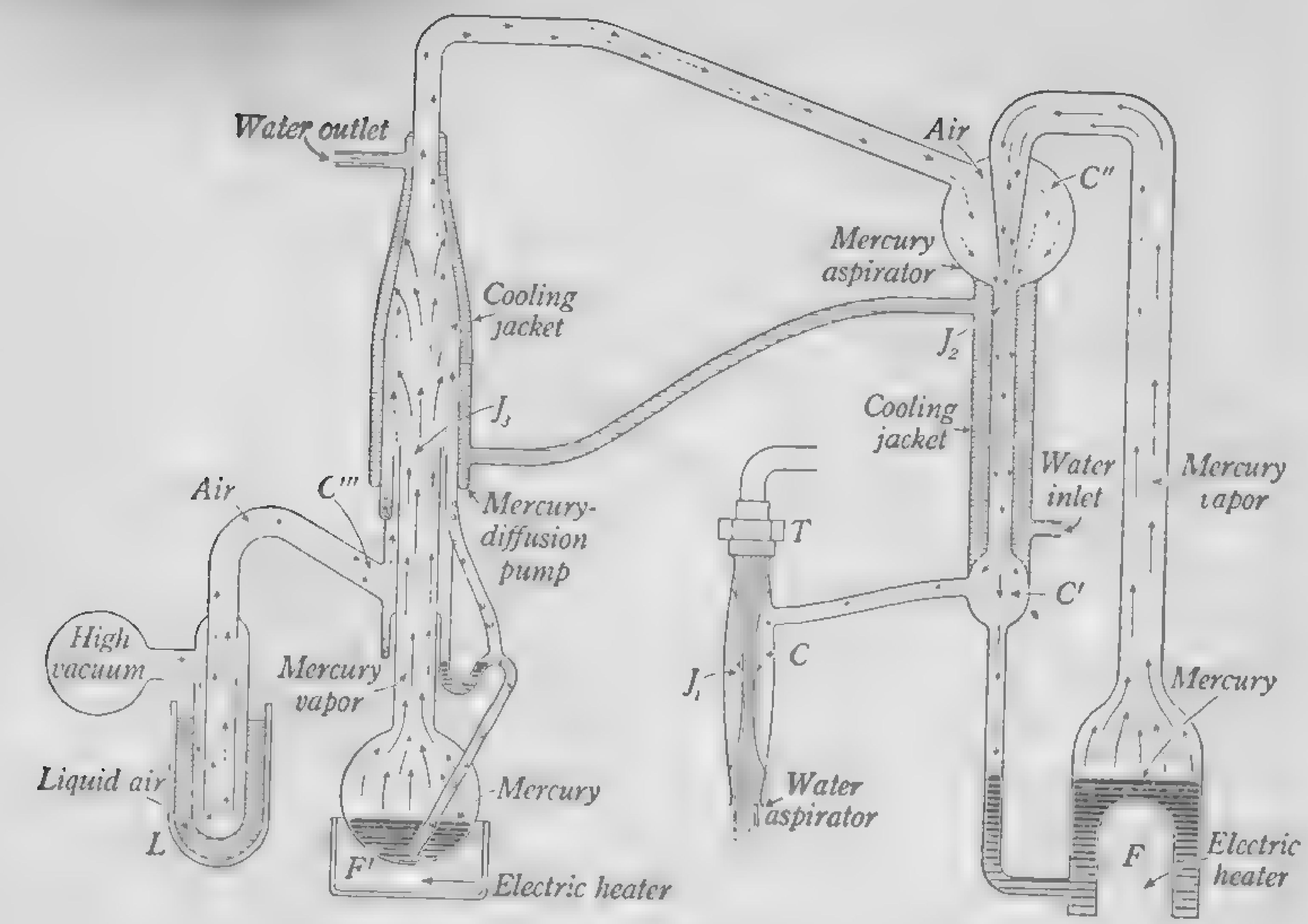
FIG. 32. A mercury barometer

At the present day geological parties ascertain differences in altitude by observing the change in the barometric pressure as they ascend or descend. A fall of 1 millimeter in the barometric height corresponds to an ascent of about 12 meters.

41. The barometer. The modern barometer (Fig. 32) is essentially nothing more nor less than Torricelli's tube. Taking a barometer reading consists simply in measuring accurately the height of the mercury column. This height varies

THE ORIGINAL MAGDEBURG HEMISPHERES

This picture is on the cover of the book which describes the experiments of Otto von Guericke. In the presence of Emperor Ferdinand III, sixteen horses are trying to separate the Magdeburg hemispheres, after the air between them has been exhausted. These hemispheres are still preserved in the museum at Berlin. Their interior diameter is 22 inches



THE MERCURY-DIFFUSION AIR PUMP

The latest development of the air pump is shown in the accompanying diagram. It is over a million times more effective than an air pump of the mechanical kind invented by Von Guericke. The principle is as follows: The jet of water pouring out through J_1 from an ordinary water tap T entrains the air in the chamber C and thus pulls the pressure in C' down to from 10 to 15 millimeters of mercury. Next, the mercury jet J_2, produced by boiling violently the mercury above the electric furnace F, entrains the air in the chamber C'' and thus lowers the pressure in this chamber to, say, .01 millimeter of mercury. Again, the stream of mercury vapor pouring out of J_3, under the influence of the furnace F', carries with it the molecules of air coming out of C'''. Finally, the liquid-air trap freezes out the mercury vapor, some of which would otherwise find its way through C''' into the high-vacuum chamber. So little air is finally left in this high-vacuum chamber that the pressure there may be as low as a hundred-millionth of a millimeter of mercury. Pumps of this sort are now used for exhausting radio bulbs and high-vacuum rectifiers, which are becoming of very great commercial value. The credit for the invention of this form of pump belongs primarily to a fellow countryman of Von Guericke, Professor Gaede, of Freiburg, Germany. Improvements of his design, however, have been made quite independently and along somewhat different lines by the following Americans: Irving Langmuir of the General Electric Company, Schenectady; O. E. Buckley of the Western Electric Company, New York; and W. W. Crawford of the Victor Electric Company, Chicago. The particular design shown in the diagram is due to Dr. J. E. Shrader of the Westinghouse Research Laboratory, Pittsburgh

from 73 to 76.5 centimeters in localities which are not far above sea level, the reason being that disturbances in the atmosphere affect the pressure at the earth's surface in the same way in which eddies and high waves in a tank of water would affect the liquid pressure at the bottom of the tank.

The barometer does not directly foretell the weather, but it has been found that a low or rapidly falling pressure is usually accompanied (or soon followed) by stormy conditions. Hence the barometer, although it is not an infallible weather prophet, is nevertheless of considerable assistance in forecasting weather conditions some hours ahead. Further, by comparing at a central station the telegraphic reports of barometer readings made every few hours at stations all over the country, it is possible to determine in what direction the atmospheric eddies responsible for barometer changes and stormy conditions are traveling and hence to forecast the weather even a day or two in advance.

42. The first barometers. Torricelli actually constructed a barometer not essentially different from that shown in Fig. 32 and used it for observing changes in the atmospheric pressure; but perhaps the most interesting of the early barometers was that set up about 1650 by Otto von Guericke, mayor of Magdeburg, Germany (1602–1686) (see opposite page 41). He used for his barometer a water column the top of which passed through the roof of his house. A wooden image which floated on the upper surface of the water appeared above the housetop in fair weather but retired from sight in foul, a circumstance which led his neighbors to charge him with being in league with Satan.

43. The aneroid barometer. Since the mercury barometer is somewhat long and inconvenient to carry, geological and surveying parties commonly use an instrument called the *aneroid barometer*. It consists essentially of one or more air-tight cylindrical boxes, the top of each one being a metallic diaphragm which bends slightly under the influence of change in the atmospheric pressure. This motion is multiplied by a delicate system of levers and is communicated to a hand which moves over a dial whose readings are made to correspond to the readings of a mercury barometer. These instruments are made so sensitive as to indicate a change in

pressure when they are moved no farther than from a table to the floor. In the self-recording aneroid barometer, or barograph, used by the United States Weather Bureau (Fig. 33), several of the air-tight boxes are superposed for greater sensitiveness, and the pressures are recorded in ink upon paper wound about a drum. Clockwork inside the drum makes it revolve once a week. A somewhat different form of the instrument is used by aviators to record altitude.

SUMMARY. **Air has weight, 1 cubic centimeter at 0° C. weighing .001293 gram and 1 cubic foot weighing $\frac{4}{3}$ ounce. Because of its**

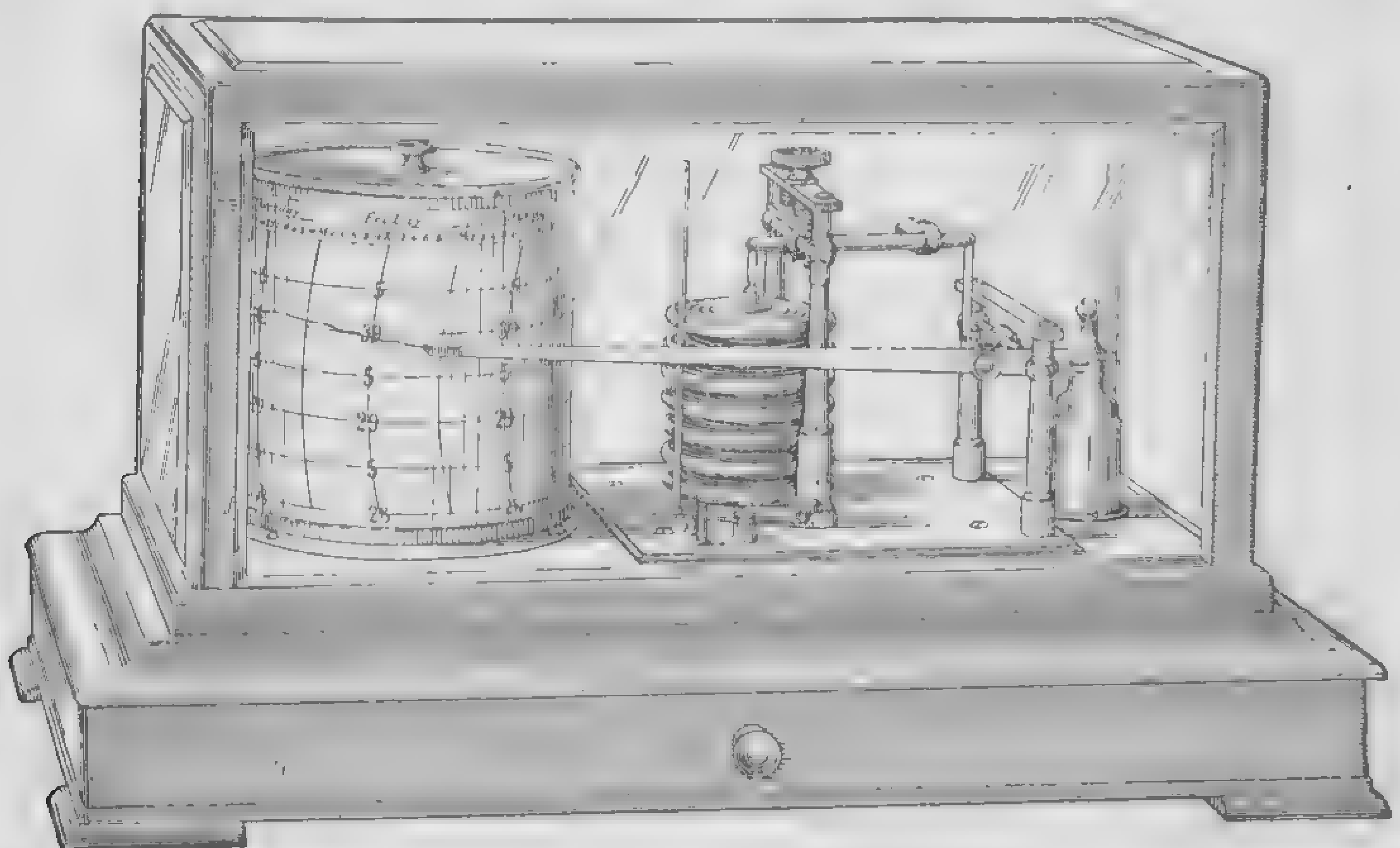


FIG. 33. The aneroid barograph

weight the atmosphere exerts a pressure at sea level of 76 centimeters (30 inches) of mercury, the equivalent of 1033.6 grams (about 1 kilogram) per square centimeter, or 14.7 pounds per square inch.

Atmospheric pressure diminishes with ascent, a fall of 1 millimeter in the barometer corresponding to an ascent of about 12 meters for relatively small distances above the sea level.

Weather forecasts are based only in part upon barometric readings. A rapidly falling barometer is usually accompanied or followed by a storm.

QUESTIONS AND PROBLEMS

1. Measure the dimensions of your classroom in feet and calculate the number of pounds of air in the room.

2. The body of the average man has 15 sq. ft. of surface. What is the total force of the atmosphere upon him? Why is he not conscious of this crushing force?

3. If a tumbler is filled with water, or partly filled, and a piece of writing paper is placed over the top, it may be inverted, as in Fig. 34, without spilling the water. Explain. What is the function of the paper?

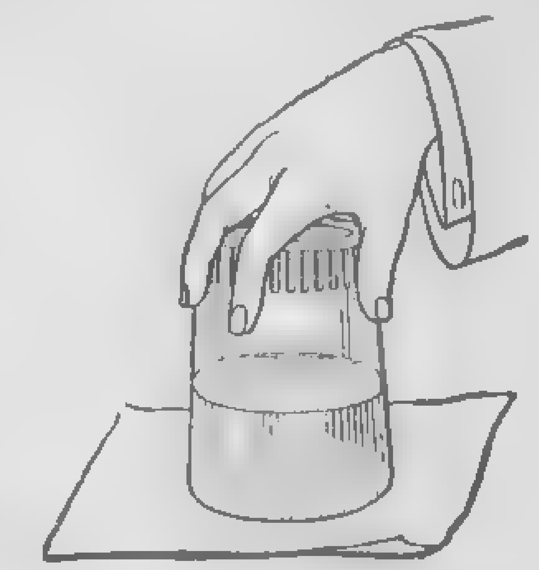


FIG. 34

4. Make a labeled drawing of a simple Torricellian barometer, naming all the parts in the diagram.

5. Would the pressure of the atmosphere hold mercury as high in a tube as large as your wrist as in one having the diameter of your finger? Explain.

6. If the variation of the height of a mercury barometer is 2 in., how far did the image rise and fall in Guericke's water barometer?

7. Give three reasons why mercury is better than water for use in barometers.

8. A balloonist once rose to such a height that his barometer read 18 cm. What was the pressure of the atmosphere?

9. If a barometer fell from 30.5 in. to 28.75 in. during the passing of a severe storm, how much did the pressure change in pounds per square inch?

10. Magdeburg hemispheres (see opposite page 34) are so called because they were invented by Otto von Guericke, who was mayor of Magdeburg. When the lips of the hemispheres are placed in contact and the air exhausted from between them, it is found very difficult to pull them apart. Why?

11. Von Guericke's original hemispheres were 22 in. in interior diameter. If the air was all removed from the interior of the hemispheres, what force in pounds was in fact required to pull them apart? (Find the atmospheric force on a circle with a radius of 11 in.)

Compressibility and Expansibility of Air

44. Incompressibility of liquids. Thus far we have found very striking resemblances between the conditions which exist at the bottom of a body of liquid and those which exist at the bottom of the great ocean of air in which we live. We now come to a most important difference. It is well known that if 2 liters of water be poured into a tall cylindrical vessel, the water will stand exactly twice as high as if the vessel contained but 1 liter; or if 10 liters be poured in, the water will stand ten times as high as if there were but 1 liter. This means that the lowest liter in the vessel is not measurably compressed by the weight of the water above it.

It has been found by carefully devised experiments that compressing forces enormously greater than these may be used without producing a marked effect; for example, when a cubic centimeter of water is subjected to the stupendous pressure of 3000 kilograms, its volume is reduced to but .90 cubic centimeter. This means that at a depth of six miles in the ocean a given volume of water is diminished only about 3 per cent. Hence we say that water, and liquids generally, are practically incompressible. Had it not been for this fact we should not have been justified in taking the pressure at any depth below the surface of the sea as the simple product of the depth by the density at the surface.

45. Compressibility of air. When we study the effects of pressure on air, we find a wholly different behavior from that described above for water. It is very easy to compress a body of air to one half, one fifth, or one tenth its normal volume, as we prove every time we inflate a pneumatic tire or cushion of any sort. Further, the *expansibility* of air (that is, its tendency to spring back to a larger volume as soon as the pressure is relieved) is proved every time a tennis ball or a football bounds, or the air rushes out from a punctured tire.

But this readiness to expand as soon as the pressure is diminished does not belong merely to air which has been

crowded into a pneumatic cushion by some sort of pressure pump; the ordinary air of the room will expand in the same way if the pressure to which it is subjected is relieved.

Thus, let a liter beaker with a sheet of rubber dam tied tightly over the top be placed under the receiver of an air pump. As soon as the pump is set into operation, the inside air will expand with sufficient force to burst the rubber or greatly distend it, as shown in Fig. 35.

Again, let two bottles be arranged as in Fig. 36, one being stoppered air-tight, and the other left uncorked. As soon as the two are placed under the receiver of an air pump and the air is exhausted, the water in A will pass over into B. When the air is readmitted to the receiver, the water will flow back. Explain.

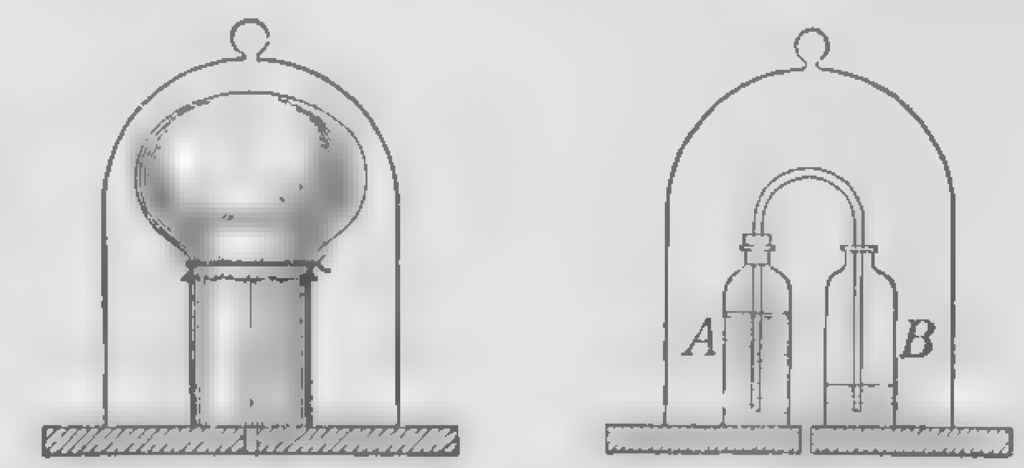


FIG. 35 FIG. 36

Illustrations of the expansibility of air

46. Why hollow bodies are not crushed by atmospheric pressure. The preceding experiments show why the walls of hollow bodies are not crushed in by the enormous forces which the weight of the atmosphere exerts against them. Thus, at normal atmospheric pressure a soap bubble $6\frac{1}{2}$ inches in diameter is under a total crushing force of one ton; but the air inside such bodies presses their walls out with as much force as the outside air presses them in. In the experiment of § 35 the inside air was removed by the escaping steam. When this steam was condensed by the cold water, the inside pressure became very small, and the outside pressure then crushed the can. In the experiment shown in Fig. 35 it was the outside pressure which was removed by the air pump, and the pressure of the inside air then burst the rubber.

47. Boyle's law. The first man to investigate the exact relation between the change in the pressure exerted by a confined body of gas and its change in volume was an Irishman, Robert Boyle (1627–1691). We shall repeat a modified form

of his experiment much more carefully in the laboratory, but the following will illustrate the method by which he discovered the important law which is now known by his name.

Let mercury be poured into a bent glass tube until it stands at the same level in the closed arm AC as in the open arm BD (Fig. 37). There is now confined in AC a certain volume of air under the pressure of one atmosphere. Call this pressure P_1. Let the length AC be measured and called V_1. Then let mercury be poured into the long arm until the level in this arm is as many centimeters above the level in the short arm as there are centimeters in the height of the barometer. The confined air is now under a pressure of two atmospheres. Call it P_2. Let the new volume $A_1C(= V_2)$ be measured. It will be found to be just half its former value.

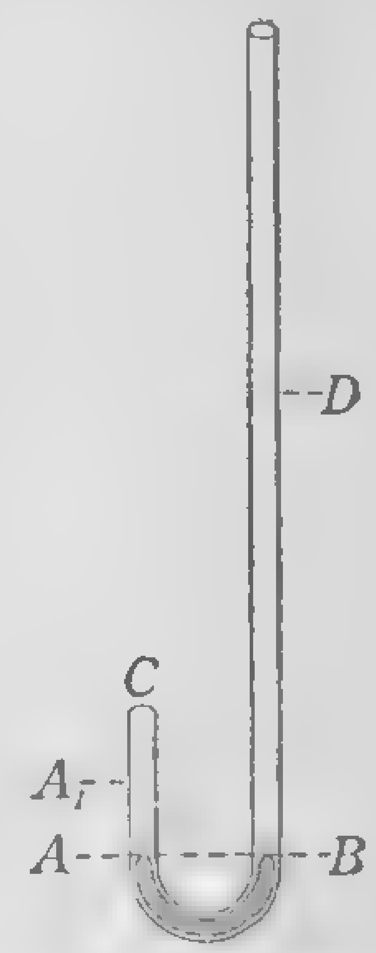


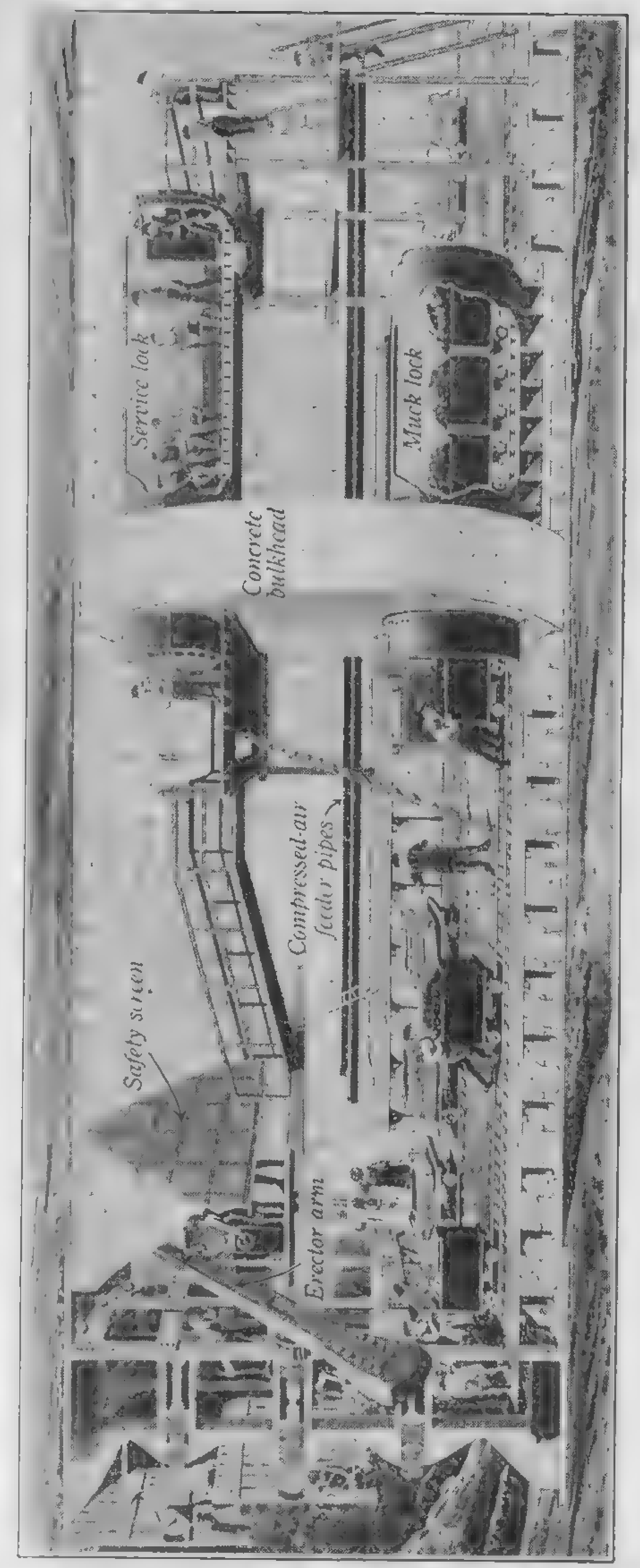
FIG. 37. Method of demonstrating Boyle's law

Hence we learn that doubling the pressure exerted upon a body of gas halves its volume. If we had tripled the pressure, we should have found the volume reduced to one third its initial value, and so on. That is, *the pressure which a given quantity of gas at constant temperature exerts against the walls of the containing vessel is inversely proportional to the volume occupied.* This may be algebraically stated as follows:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}, \text{ or } P_1V_1 = P_2V_2. \qquad (1)$$

This is Boyle's law. It may also be expressed in slightly different form. Doubling, tripling, or quadrupling the pressure must double, triple, or quadruple the *density,* since the volume is made only one half, one third, or one fourth as much, while the mass remains unchanged. Hence *the pressure which a gas exerts at constant temperature is directly proportional to its density.**

* A laboratory experiment on Boyle's law should follow this discussion. See, for example, Experiment 8 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.



UNDER-WATER TUNNEL CONSTRUCTION

In constructing subaqueous tunnels, the workers are compelled to operate under an air pressure great enough to withstand the pressure which would force earth and muck into the space where they work. As material is removed (see left end of picture), powerful jacks press forward a cylindrical shield, inside of which the tunnel lining of cast-iron segments is built up. A concrete bulkhead separates the compressed-air working chamber at the left from the space at the right, where atmospheric pressure exists. To enter the high-pressure compartment, the men pass first into the service lock, and remain there for several minutes, while the air pressure upon them is gradually increased. This is called "compressing" the men. The blood in this way becomes charged with dissolved air which enters by way of the lungs. To leave the high-pressure compartment, the men again enter the service lock, while the pressure is gradually lowered to atmospheric to permit the excess dissolved gases to leave the blood by way of the lungs. If this "decompressing" is done too rapidly, the dissolved gases escape as bubbles within the blood vessels, causing intense pain and sometimes death. Small cars laden with diggings of rock, earth, and muck are taken out through the locks as shown at the bottom. (Courtesy of the *Popular Science Monthly*)

OTTO VON GUERICKE (1602–1686)

German physicist, astronomer, and man of affairs; mayor of Magdeburg; invented the air pump in 1650, and performed many new experiments with liquids and gases; discovered electrostatic repulsion; constructed the famous Magdeburg hemispheres which eight teams of horses could not pull apart (see opposite page 34)

48. Measurement of gas pressure. For measuring gas and steam pressures various types of gauges are used, the Bourdon being one of the best. Fig 38 (2) shows a simple form of this gauge for use with automobile tires. A flattened tube (Fig. 38 (1)) is bent into the form of an arc, so that when air under pressure enters it the tube tends to straighten. This causes the rack R to turn the pinion P, to which the pointer is attached. These gauges, as well as steam gauges, record whatever pressure exists *in excess of the atmospheric pressure.* In general, *absolute* (*or total*) *pressure equals gauge pressure + 15 pounds per square inch at sea level.**

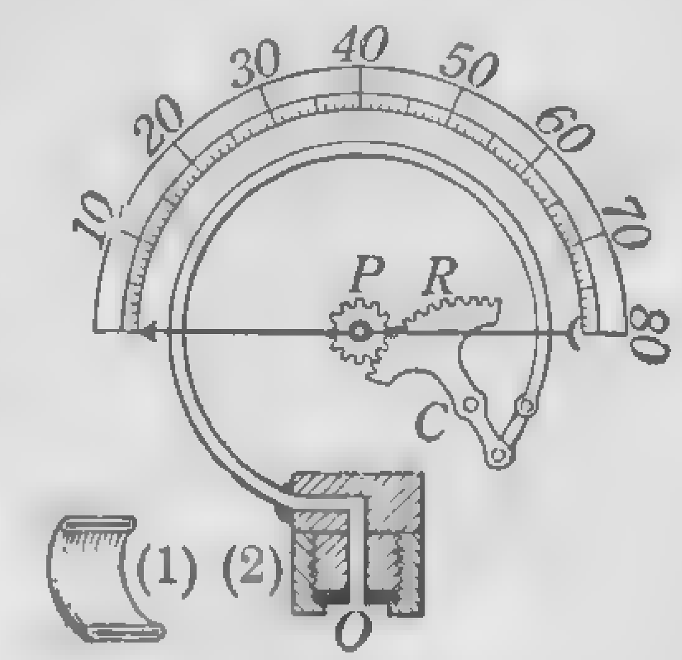


FIG. 38. Interior of Bourdon type of tire pressure gauge

49. The extent and character of the earth's atmosphere. From the facts of compressibility and expansibility of air we may know that the air, unlike the sea, must become less and less dense as we ascend from the bottom toward the top. Thus, at the summit of Mont Blanc, an altitude of about three miles, where the barometer height is but 38 centimeters, or one half its value at sea level, the density also must, by Boyle's law, be just one half as much as at sea level. How rapidly both density and pressure decrease with altitude is indicated by the curve in Fig. 39.

No balloonist has ascended higher than 8 miles. In 1862 a height of approximately 7 miles was attained by the two daring English aëronauts Glaisher and Coxwell. At this altitude the barometric height is but about 7 inches. Both aëronauts lost the use of their limbs, and Mr. Glaisher became unconscious. Mr. Coxwell barely succeeded in grasping with his teeth the rope which opened a valve and caused the balloon to descend. Again, on May 4, 1927, Captain Gray

*It is recommended that laboratory work on the use of manometers accompany this discussion. See, for example, Experiment 9, of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

of the United States army rose without injury to a height of about 8 miles (42,470 feet), his success being due to the artificial inhalation of oxygen. The French aviator Callizo, at Villaconblay, France, on October 10, 1924, ascended in an airplane to a height of 40,820 feet ($7\frac{3}{4}$ miles). The temperature recorded was about 100° F. below freezing.

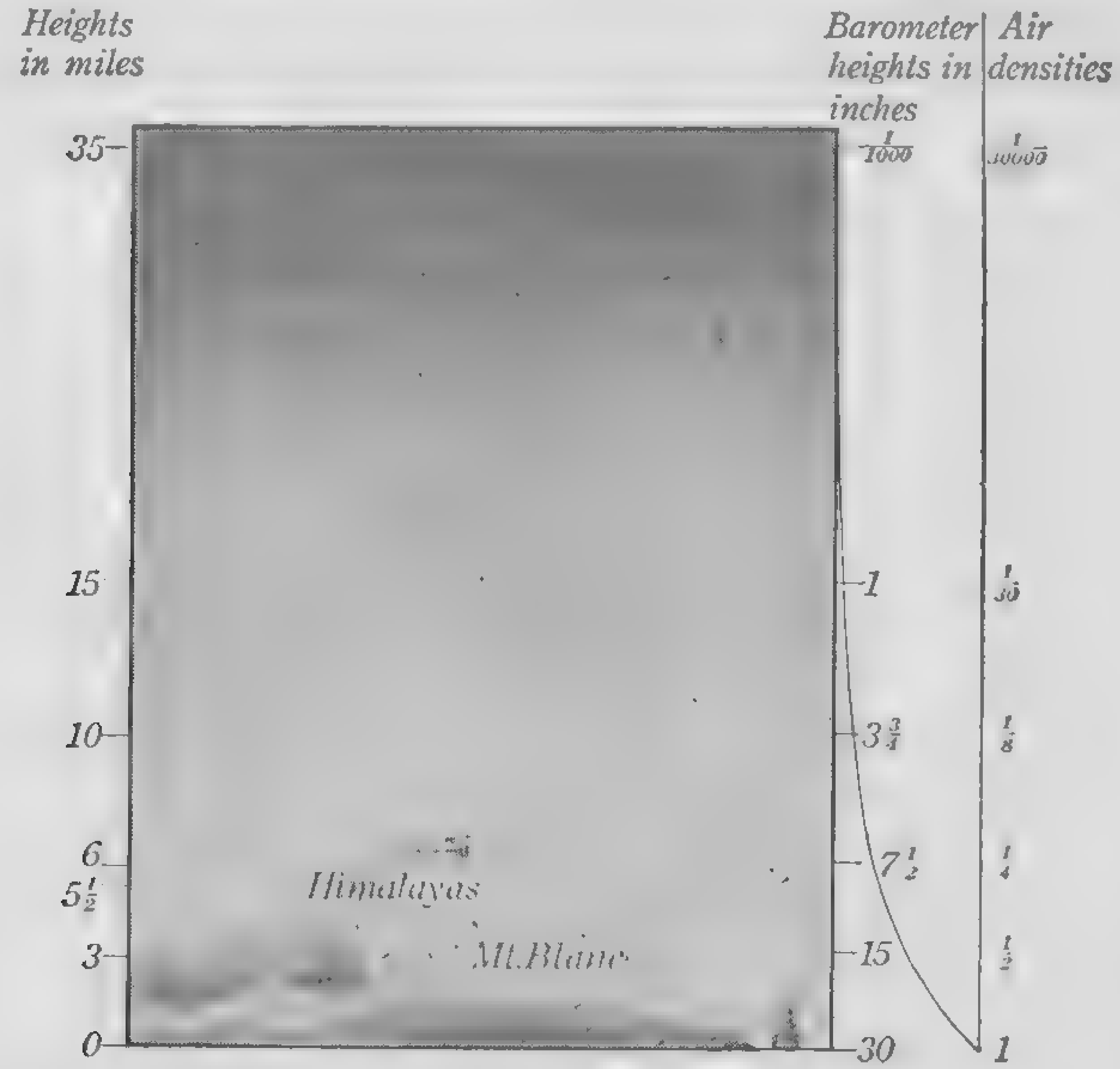


FIG. 39. Extent and character of atmosphere

By sending up self-registering thermometers and barometers in balloons which burst at great altitudes (the instruments being protected by parachutes from the dangers of rapid fall), the atmosphere has been explored to a height of 35,080 meters (21.8 miles), this being the height attained on December 7, 1911, by a little balloon which was sent up at Pavia, Italy. These extreme heights are calculated from the indications of the self-registering barometers.

At a height of 35 miles the density of the atmosphere is estimated to be but $\frac{1}{30000}$ as great as at sea level. By calcu-

lating how far below the horizon the sun must be when the last traces of color disappear from the sky, we find that at a height as great as 45 miles there must be air enough to reflect some light. How far beyond this an extremely rarefied atmosphere may extend, no one knows. It has been estimated at all the way from 100 to 500 miles. These estimates are based on observations of the height at which meteors first become visible, on the height of the aurora borealis, and on the darkening of the surface of the moon just before it is eclipsed by the shadow of the solid earth.

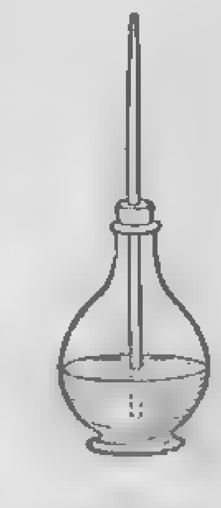


FIG. 40

SUMMARY. Liquids, being practically incompressible, exert pressure proportional to depth below the free surface.

Gases, being highly compressible, do not follow the depth-pressure law.

Boyle's law. **The pressure exerted by a given mass of gas at constant temperature is inversely proportional to its volume or directly proportional to its density.**

QUESTIONS AND PROBLEMS

1. Blow as hard as possible into the tube of the bottle shown in Fig. 40. Then withdraw the mouth and explain all the effects observed.

2. What sort of change in volume do the bubbles of air which escape from a diver's suit experience as they ascend to the surface?

3. With the aid of the experiment in which the rubber dam was burst under the exhausted receiver of an air pump, explain why high mountain climbing often causes pain and bleeding in the ears and nose.

4. Pressure tests for boilers or steel tanks of any kind are always made by filling them with water rather than with air. Why?

5. The deepest sounding in the ocean is about 6 mi. Find the pressure in tons per square inch at this depth. (Specific gravity of ocean water = 1.026.) Will a pebble thrown overboard reach the bottom? Explain.

6. Why must the cap be removed from a kerosene can in order to secure a proper flow from the spout?

7. If 100 cu. ft. of hydrogen gas at normal pressure are forced into a steel tank having a capacity of 5 cu. ft., what is the absolute gas pressure in pounds per square inch? What is the gauge pressure?

8. A gas cylinder 5 ft. long and 1 sq. ft. in cross section contains gas at a gauge pressure of 210 lb. per square inch. How many cubic feet would this gas occupy at normal atmospheric pressure?

9. There is a pressure of 80 cm. of mercury on 1000 cc. of gas. What pressure must be applied to reduce the volume to 600 cc. if the temperature is kept constant?

10. An automobile tire having a capacity of 1500 cu. in. is inflated to a gauge pressure of 35 pounds per square inch. What is the density of the air within the tire? To what volume would the air expand if there should be a "blow-out"?

11. A glass tube 25 in. long and closed at the upper end is attached to the sounding lead of a ship. On drawing the lead from the bottom of the ocean, the sea water is found to have wet 24 in. of the inner surface of the tube. How many atmospheres of pressure acted upon the air inclosed in the tube? How many were due to the water? How many fathoms (a fathom = 6 ft.) deep was the ocean (the density of ocean water being 64 lb. per cubic foot)?

12. Under ordinary conditions a gram of air occupies about 800 cc. Find what volume a gram will occupy at the top of Mont Blanc (altitude 15,781 ft.), where the barometer indicates that the pressure is only about one half what it is at sea level.

13. The mean density of the air at sea level is about .0012. g. per cubic centimeter. What is its density at the top of Mont Blanc? What fractional part of the earth's atmosphere has one left beneath him when he ascends to the top of this mountain?

Pneumatic Appliances

50. The siphon. Let a rubber or glass tube be filled with water and then placed in the position shown in Fig. 41. Water will be found to flow through the tube from vessel *A* into vessel *B*. If *B* is then raised until the water in it is at a higher level than that in *A*, the direction of flow will be reversed. This instrument, which is called the *siphon*, is very useful for removing liquids from

vessels which cannot be overturned, or for drawing off the upper layers of a liquid without disturbing the lower layers. Many commercial applications of it are found in various siphon flushing systems.

The explanation of the action of the siphon is readily seen from Fig. 41. Since the tube *acb* is full of water, water must evidently flow through it if the force which pushes it one way is greater than that which pushes it the other way. Now the upward pressure at *a* is equal to the atmospheric pressure minus the downward pressure of the water column *ad*, and the upward pressure at *b* is the atmospheric pressure minus the downward pressure of the water column *bc*. Hence the pressure at *a* exceeds the pressure at *b* by the pressure of the water column *fb*. The siphon will evidently cease to operate when the water is at the same level in the two vessels, since then $fb = 0$, and the forces acting at the two ends of the tube are therefore equal and opposite. It will also cease to act when the bend *c* is more than 34 feet above the surface of the water in *A*, atmospheric pressure being unable to raise water to a height greater than this in either tube.

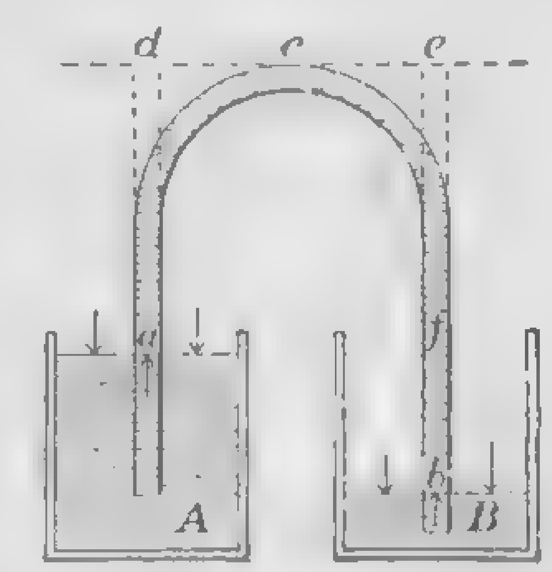


Fig. 41. The siphon

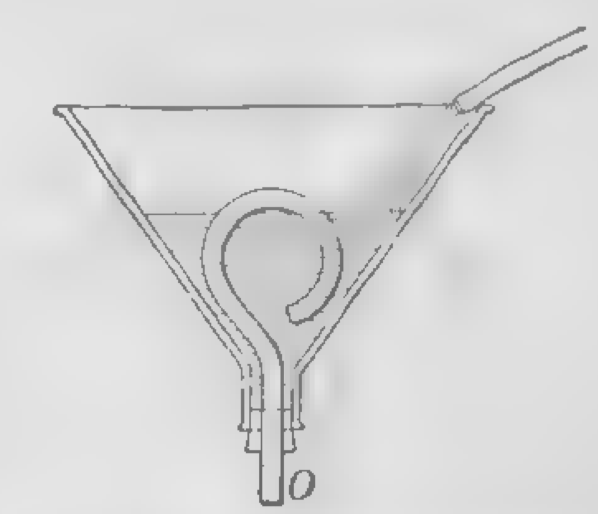


Fig. 42. The intermittent siphon

Would a siphon flow in a vacuum?

51. The intermittent siphon. Fig. 42 represents an intermittent siphon. If the vessel is at first empty, to what level must it be filled before the water will flow out at *o*? To what level will the water then fall before the flow will cease?

52. The air pump. The air pump was invented in 1650 by Otto von Guericke, who deserves the greater credit since he was apparently altogether without knowledge of the discoveries which Galileo, Torricelli, and Pascal had made a few

years earlier in regard to the character of the earth's atmosphere. A simple form of such a pump is shown in Fig. 43. When the piston is raised, the air from the receiver *R* expands into the cylinder *B* through the valve *A*. When the piston descends, it compresses this air and thus closes the valve *A*, opening, in turn, the exhaust valve *C*. Thus, with each double stroke a certain fraction of the air contained in the receiver is transferred from *R* through the cylinder to the outside. In many pumps the valve *C* is located in the piston itself.

53. The compression pump. A compression pump is used for compressing a gas into a container. If the pump shown in Fig. 43 is detached from the receiver plate, and the vessel to receive the gas is attached at *C*, we have a compression pump.

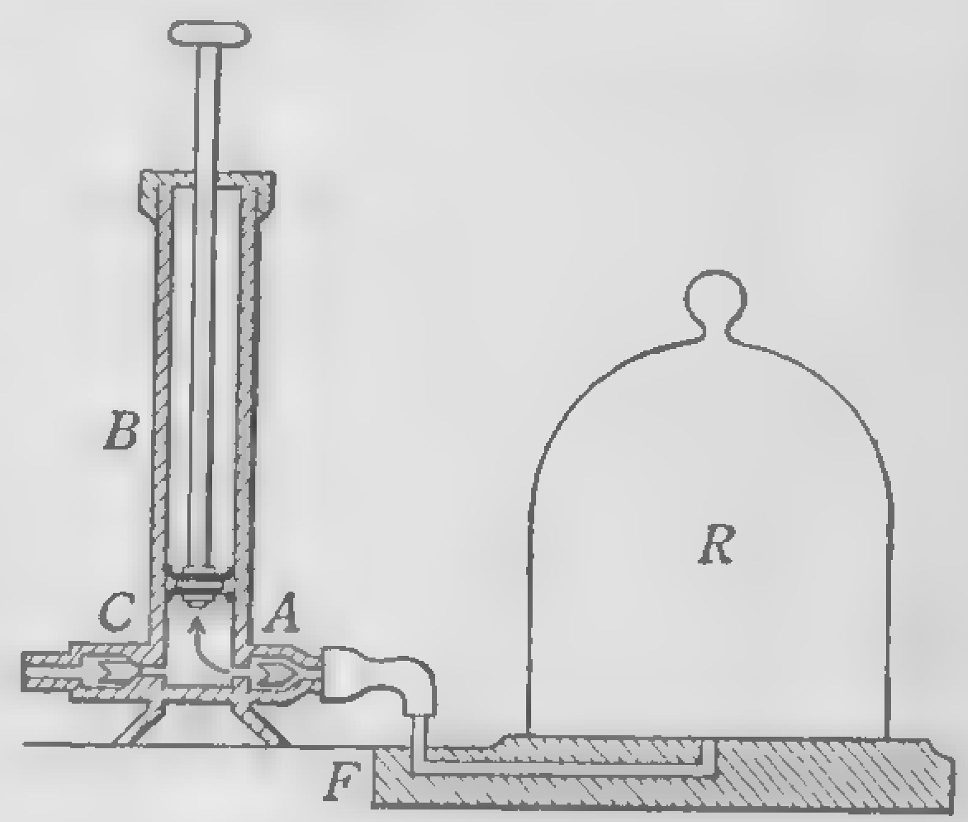


FIG. 43. A simple air pump

Compressed air finds so many applications in such machines as air drills (used in mining), air brakes, air motors, etc. that the compression pump must be looked upon as of much greater importance industrially than the exhaust pump. (See opposite page 40 for tunnel construction.)

54. The lift pump. The common water pump, shown in Fig. 44, has been in use at least since the time of Aristotle (fourth century B. C.) It will be seen from the figure that it is nothing more nor less than a simplified form of air pump. In fact, in the earlier strokes we are simply exhausting air from the pipe below the valve *b*. Water could never be obtained at *S*, even with a perfect pump, if the valve *a* did not work within 34 feet of the surface of the water in *W*. Why? On account of mechanical imperfections this limit is usually about 28 feet instead of 34. Let the student analyze, stroke by stroke, the operation of pumping water from a well

with the pump of Fig. 44. Why will pouring in a little water at the top — that is, "priming" — often assist greatly in starting such a pump? Pumps used in very deep wells are constructed with long plunger rods to bring the piston *P* to within the necessary distance of the water for successful operation.

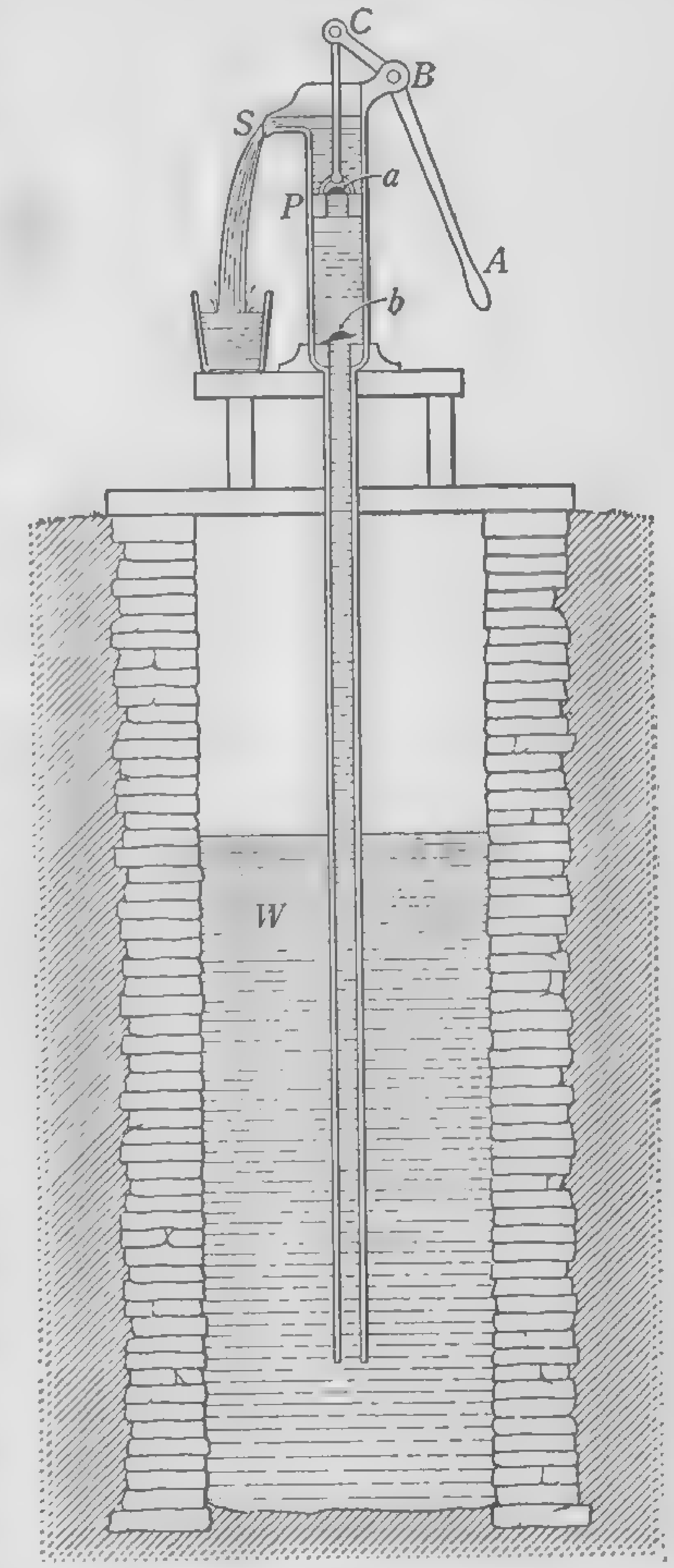


FIG. 44. The lift pump

55. The force pump. Fig. 45 illustrates the construction of the force pump, a device at least two thousand years old. The force pump is commonly used when it is desired to deliver water at a point higher than the position at which it is convenient to place the pump itself. Let the student analyze the action of the pump from a study of the diagram.

To make the flow of water in the pipe *HS* continuous during the upstroke, an air chamber is inserted between the valve *a* and the discharge point. As the water is forced violently into this chamber by means of the downward motion of the piston, it compresses the confined air. It is the reaction of this compressed air that is directly responsible for the flow in the discharge tube; and as this reaction is continuous, the flow is continuous.

56. The Cartesian diver. Descartes (1596–1650), the great French philosopher, invented an odd device which illustrates at the same time the principle of the transmission of pressure by liquids, the principle of Archimedes, and the compressibility of gases. A hollow glass image in human shape (see Fig. 46 (1)) has an opening in the lower end. It is filled in part with water and in part with air, so that it will just float. By pressing on the rubber diaphragm at the top of the vessel it may be made to sink or rise at will. Explain. If the diver is not available, a small bottle or test tube (Fig. 46 (2)) may be used instead; it works equally well and brings out the principle even better.

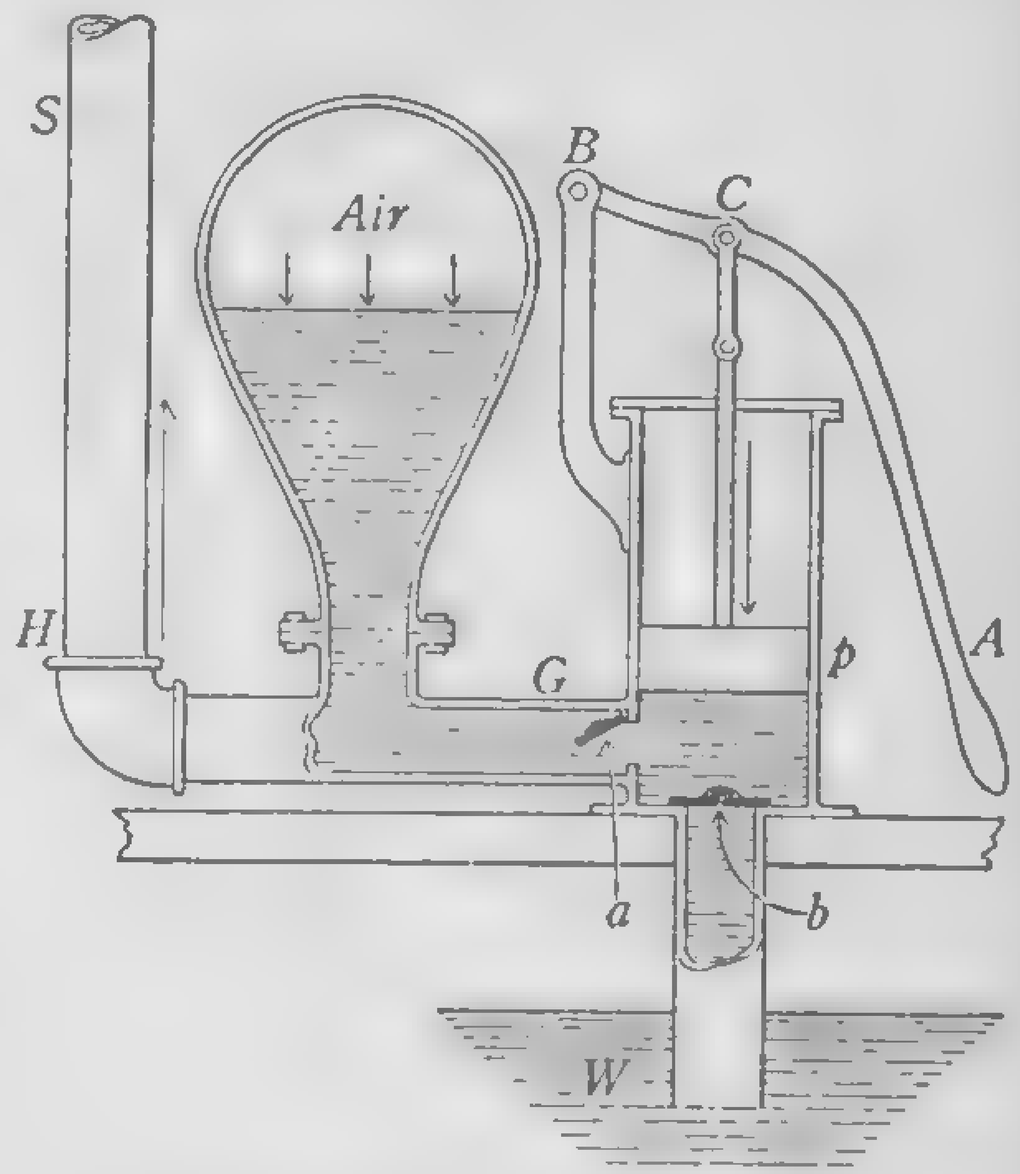


FIG. 45. The force pump

The modern submarine (see opposite page 25) is essentially nothing but a huge Cartesian diver propelled, above water, by oil or steam engines and, when submerged, by electric motors driven by storage batteries. The volume of air in its chambers is changed by forcing water in or out, and it dives by a combined use of the propeller and the horizontal rudders.

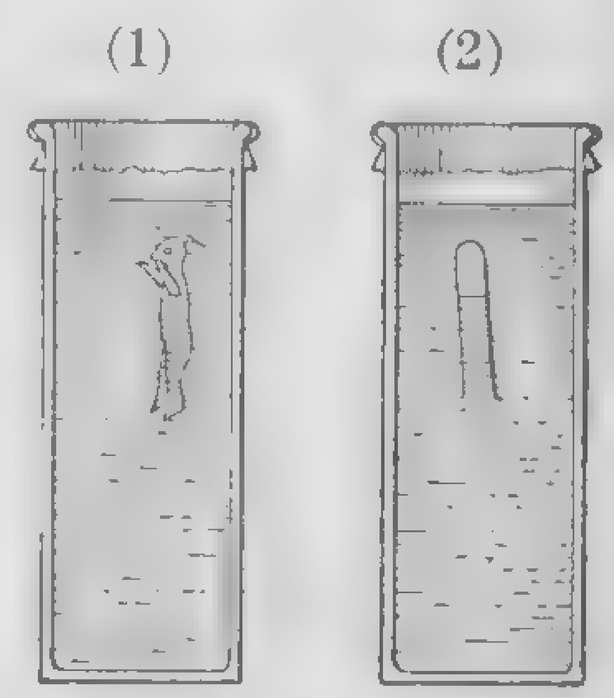


FIG. 46. The Cartesian diver

57. The balloon. A reference to the proof of Archimedes' principle (see § 29, p. 24) will show that it must apply as well to gases as to liquids. Hence, *any body immersed in air is buoyed up by a force which is equal to the weight of the displaced air.* The body will there-

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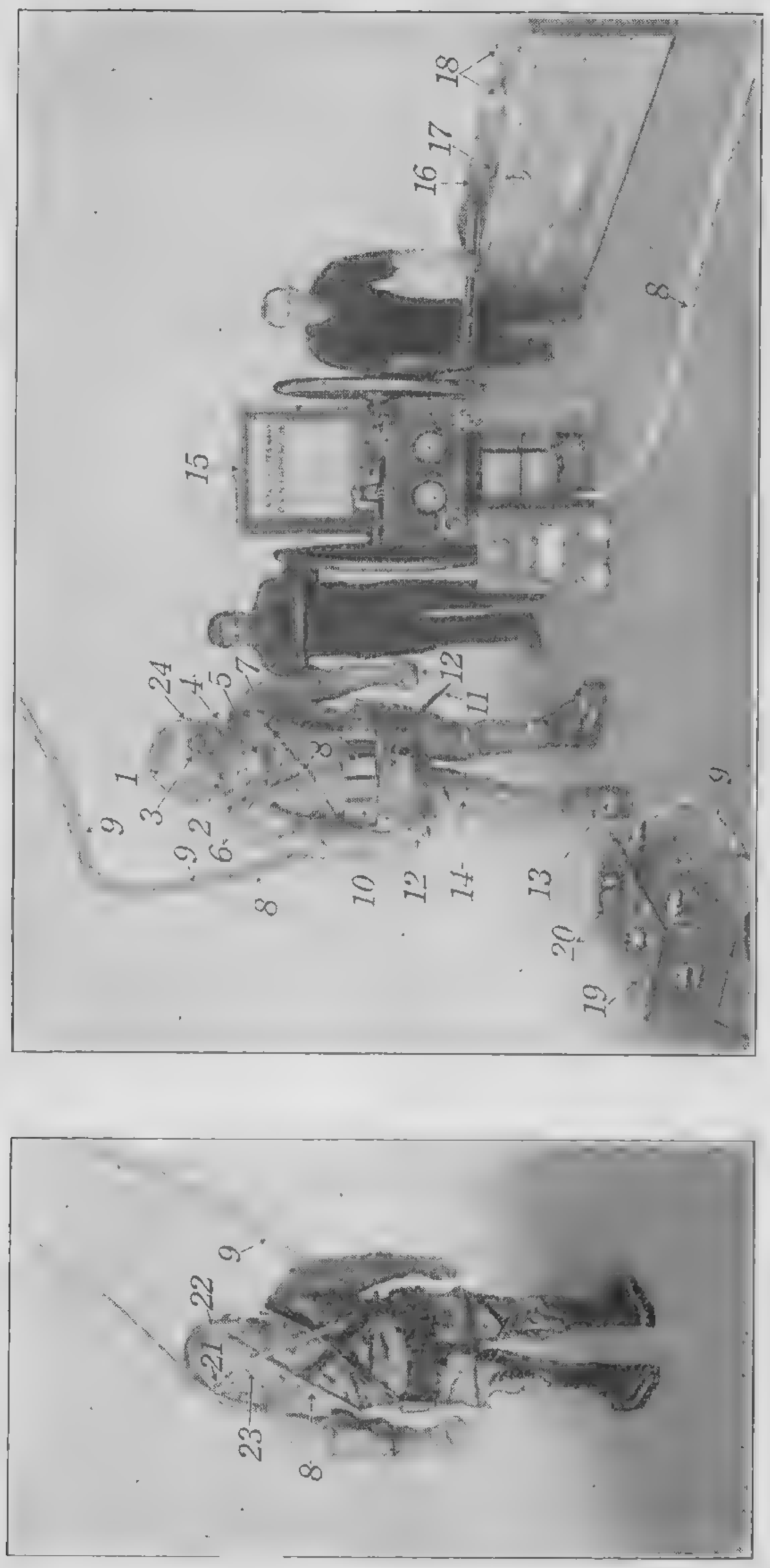
BRITISH DIRIGIBLE AIRSHIP *R-34* ARRIVING IN AMERICA

The *R-34* photographed just as her gondola touched the ground at Mineola, Long Island, July 6, 1919, after the first transatlantic flight of a lighter-than-air machine. This was the longest air flight in history, covering 3200 nautical miles, from Scotland to New York, in exactly 4½ days, or 108 hours. On account of severe weather conditions and the route taken the actual distance covered was 6300 nautical miles. She returned to Scotland in 75 hours. The characteristics of this historic airship were length, 672 feet; height, 90 feet; diameter, 79 feet; 5 engines, 250 to 275 H. P. each (normal R.P.M. = 1600); total H.P., 1250 to 1375; 19 gas bags of goldbeater's skin (calf's intestine); capacity, 2,000,000 cubic feet; each engine, 12 cylinders; propellers geared to ¼ engine speed; frame made of duralumin (= 95 per cent Al); catwalk inside envelope, 600 feet; total weight, 59 gross tons, of which 16 tons was gasoline (= 4900 gallons); could rise to a height of 14,000 feet



THE DIVER'S OUTFIT

1, helmet (spun copper); *2*, air-escape valve; *3*, hinged front window; *4*, spitcock; *5*, breastplate with collar straps; *6*, breastplate wing nuts; *7*, air-inlet control valve; *8*, air hose; *9*, telephone cable; *10*, belt with lead weights; *11*, double-edged knife in case; *12*, rubber gloves; *13*, lead-soled shoes; *14*, suit (rubberized canvas); *15*, diver's air pump; *16*, helmet and outfit chest; *17*, wrench for tightening wing nuts; *18*, cuff expanders; *19*, telephone box; *20*, tender's telephone set; *21*, telephone gooseneck connection; *22*, air gooseneck connection; *23*, safety helmet lock; *24*, diver's combination transmitter and receiver set into helmet. (Courtesy of Schrader's Sons)

fore rise if its own weight is less than the weight of the air which it displaces. When these weights become equal, the body floats.

A balloon is a large silk bag impregnated with rubber and usually filled either with hydrogen or with common illuminating gas. The former gas weighs about .09 kg. per cubic meter, and common illuminating gas weighs about .75 kg. per cubic meter. It will be remembered that ordinary air weighs about 1.20 kg. per cubic meter. It will be seen, therefore, that the lifting force of hydrogen per cubic meter (namely, $1.20 - .09 = 1.11$) is more than twice the lifting force of illuminating gas ($1.20 - .75 = .45$). From the weights given above it is easy to calculate the lifting power of any balloon whose volume is known.

Ordinarily a balloon is not completely filled at the start; for if it were, since the outside pressure is continually diminishing as it ascends, the pressure of the inside gas would subject the bag to enormous strain and would surely burst it before it reached any considerable altitude. But if it is but partly inflated at the start, it can increase in volume as it ascends by simply inflating to a greater extent. Thus, a balloon which ascends until the pressure is but 7 cm. of mercury should be only about one-fourth inflated when it is at the surface.

FIG. 47. The parachute

The parachute (Fig. 47) is a huge, umbrella-like affair with which the aëronaut may descend in safety to the earth. After opening, it descends very slowly on account of the enormous surface exposed to the air. A hole in the top allows air to escape slowly and thus keeps the parachute upright.

58. Helium balloons. One of the striking results of the World War was the development of the helium balloon. Helium is a non-inflammable gas twice as dense as hydrogen and having a lifting power .92 as great. It is so rare an element that before the war not over 100 cu. ft. had been collected by anyone. Its pre-war price was $1700 per cubic foot. It is now being produced at a cost of ten cents a cubic foot from the gas wells of Texas and Oklahoma. The production of a balloon gas that assures safety from fire opens up a new era for the dirigible balloon (see opposite page 48).

59. The diving suit. For most under-water work except that of heavy engineering the diving suit (see opposite page 49) is used. This suit is made of rubber and has a metal helmet. The diver is usually connected with the surface by a tube through which air is forced down to him. It passes out into the water through a valve in his suit. But sometimes the diver is entirely independent of the surface, carrying air under a pressure of about 40 atmospheres in a tank on his back. This air is allowed to escape gradually through the suit and out into the water through a valve as fast as the diver needs it. When he wishes to rise to the surface, he simply admits enough air to his suit to make him float.

In all cases the diver is subjected to the pressure existing at the depth at which the suit communicates with the outside water. Divers seldom work at depths greater than 60 feet, and 80 feet is usually considered the limit of safety. But Chief Gunner's Mate Frank Crilley, investigating the sunken United States submarine *F–4* at Honolulu in 1915, descended to a depth of 304 feet.

The diver experiences pain in the ears and above the eyes when he is ascending, but not when at rest. This is because it requires some time for the air to escape from the interior cavities of the body and establish equal pressure in both directions.

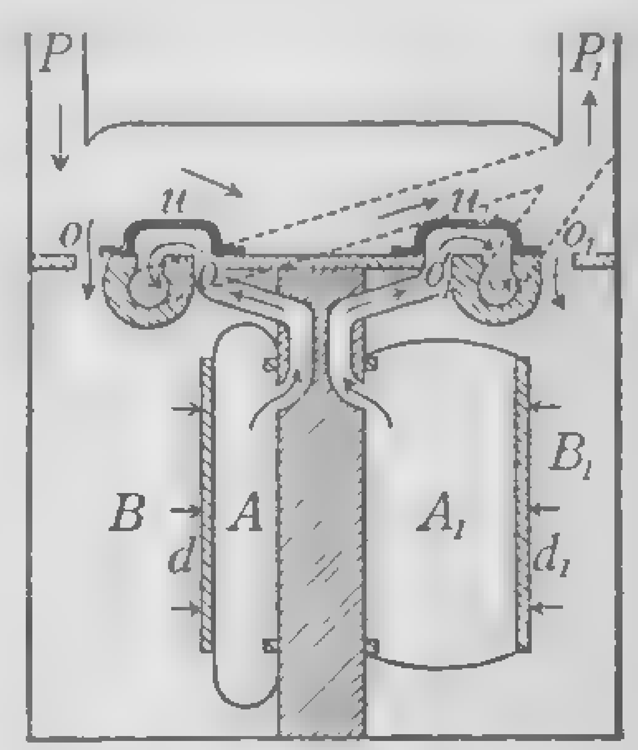


FIG. 48. The gas meter

60. The gas meter. Gas from the city supply enters the meter through P (Fig. 48) and passes through the openings o and o_1 into the compartments B and B_1 of the meter. Here its pressure forces in the diaphragms d and d_1. The gas already contained in A and A_1 is therefore pushed out to the burners through the openings o' and o'_1 and the pipe P_1. As soon as the diaphragm d has moved as far as it can to the right, a lever which is worked by the movement of d causes the slide valve u to move to the left, thus closing o and shutting off connection between P and B, but at the same time opening o' and allowing the gas from P to enter compartment A through o'. A quarter of a cycle later u_1 moves to the right and connects A_1 with P and B_1 with P_1. If u and u_1 were set so as to work exactly together, there would be slight fluctuations in the gas pressure at P_1. The movement of the diaphragms is recorded by a clockwork device the dials of which indicate the number of cubic feet of gas which have passed through the meter.

SUMMARY. The siphon flows because of unbalanced pressures within its unequal arms.

An air pump is a device for removing air from a vessel by taking advantage of the natural tendency of gases to expand.

A lift pump must have its piston work within the limits of the height to which atmospheric pressure can raise a column of water.

A force pump can deliver water to any height.

Balloons rise or descend in accordance with Archimedes' law.

Divers are subject to the laws of liquid pressure and to Archimedes' law.

QUESTIONS AND PROBLEMS*

1. Let a siphon of the form shown in Fig. 49 be made by filling a flask one-third full of water, closing it with a cork through which pass two pieces of glass tubing, as in the figure, and then inverting so that the lower end of the straight tube is in a dish of water. If the bent arm is of considerable length, the fountain will play forcibly and continuously until the dish is emptied. Explain.

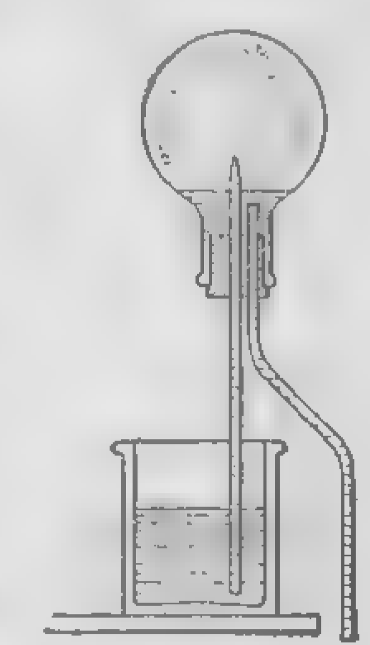


FIG. 49

2. A water tank 8 ft. deep, standing some distance above the ground and closed everywhere except at the top, is to be emptied. The only means of emptying it is a flexible tube. (1) What is the most convenient way of using the tube, and how could it be set in operation? (2) How long must the tube be, in order to empty the tank completely?

3. Kerosene has a specific gravity of .8. Over what height can it be siphoned at normal pressure?

4. Describe the construction and explain the operation of the piston air pump, employed for exhausting a receiver.

* Supplementary questions and problems for Chapter III are given in the Appendix.

5. If the cylinder of an air pump is of the same size as the receiver, what fractional part of the air is removed by one complete stroke? What fractional part is left after three strokes? after ten strokes?

6. If the cylinder of an air pump is one third the size of the receiver, what fractional part of the original air will be left after 5 strokes? What will be the reading of a barometer within the receiver, the outside pressure being 76?

7. Theoretically, can a vessel ever be completely exhausted by an air pump, even if the pump be mechanically perfect?

8. Draw a diagram of a lift pump on the upstroke. What causes the water to rise in the pipe? What happens on the downstroke?

9. Draw a diagram of a force pump with an air dome, showing conditions on the downstroke. What happens on the upstroke?

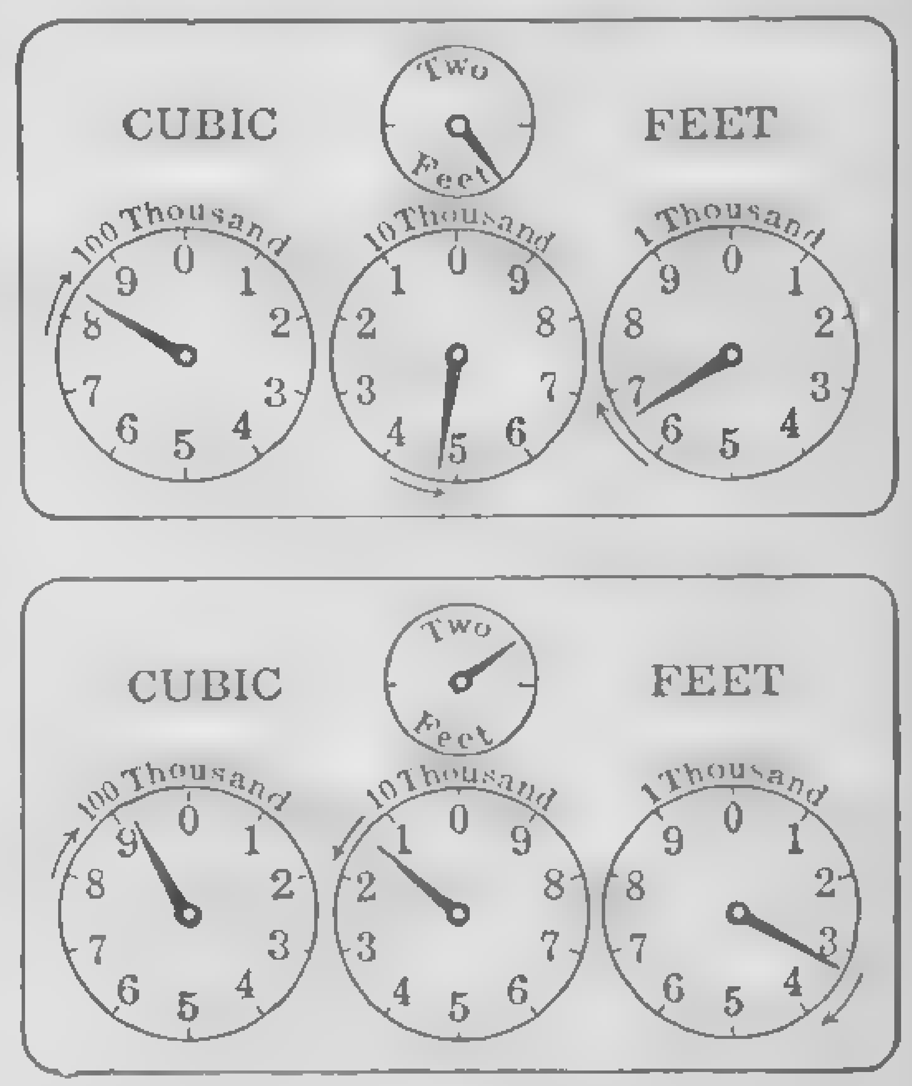


FIG. 50. The dials of a gas meter

10. At sea level what is the greatest height above the surface of the gasoline in a reservoir at which the upper piston of a perfect lift pump could operate? (The specific gravity of gasoline = .75.)

11. What determines how far a balloon will ascend? Explain by the principle of Archimedes.

12. If a balloonist wishes to descend, he causes the gas bag to become smaller by letting out some of the gas through a valve at the top. Why does this allow the balloon to drop to a lower level? How may he again ascend?

13. Explain by reference to the weight of a balloon and the upward and downward forces of the atmosphere upon it why it rises.

14. How many of the laws of liquids and gases do you find illustrated in the experiment of the Cartesian diver?

15. Hydrogen is lighter than air. Would pumping more of it into a balloon already expanded to its maximum capacity increase the lifting power of the balloon? Explain fully.

16. A liter of air weighs 1.29 g. and a liter of helium 0.18 g. at 0° C. If a small rubberized-silk balloon weighing 10 g. is filled with 40 l. of helium, what is its lifting power?

17. If air is forced into a caisson until the level of the water within it is 1033 cm. beneath the surface of the river, to what fraction of its initial volume has the inclosed air been reduced? (1033 g. per square centimeter = 1 atmosphere.)

18. In Fig. 50 the upper figure shows a reading of 84,600 cu. ft. of gas. The lower figure shows the reading of the meter a month later. What was the amount of the bill for the month at 80 cents per 1000 cu. ft.? Draw a diagram of the meter dials to represent 49,200 cu. ft.

19. Pneumatic dispatch tubes are now used in many large stores for the transmission of small packages. An exhaust pump is attached to one end of the tube in which a tightly fitting carriage moves, and a compression pump to the other. If the air is half exhausted on one side of the carriage and has twice its normal density on the other, find the propelling force acting on the carriage when the area of its cross section is 50 sq. cm.

20. A submarine weighs 1800 tons when its submerging tanks are empty, and in that condition 10 per cent by volume of the submarine is above water. What weight of water must be let into the tanks in order just to submerge the boat?

CHAPTER IV

MOLECULAR MOTIONS

Kinetic Theory of Gases

61. Molecular constitution of matter. In order to account for some of the simplest facts in nature — for example, the fact that two substances often apparently occupy the same space at the same time, as when two gases are crowded together in the same vessel or when sugar is dissolved in water — it has been found that all substances are composed of very minute particles called *molecules*. Spaces exist between these molecules; so that when one gas enters a vessel which is already full of another gas, the molecules of the one scatter themselves about among the molecules of the other. Since molecules cannot be seen with the most powerful microscopes, it is evident that they must be very minute. The number of them contained in a cubic centimeter of air at normal temperature and normal pressure is twenty-seven billion billion (27×10^{18}). It has been estimated that this is approximately the number of grains of sand required to make a beach 1 mile long, 1000 feet wide, and 3 feet deep. It would take as many as a thousand molecules laid side by side to make a speck long enough to be seen with the best microscopes.

62. Evidence for molecular motions in gases. Certain very simple observations lead us to the conclusion that the molecules of gases, even in a still room, must be in continual and rapid motion. Thus, if a little ammonia, or any gas of powerful odor, is introduced into a room, in a very short time it will have become perceptible in all parts of the room. This shows clearly that enough of the molecules of the gas to affect the olfactory nerves must have found their way across the room.

ALBERT EINSTEIN (1879-   )

Most creative of living theoretical physicists; developed in 1905 the theory of Brownian movements and pointed the way thereby to the experimental verification of the molecular and kinetic hypothesis; first set up, also in 1905, the so-called Einstein photo-electric equation, which involves a new conception as to the nature of light, an equation subsequently completely verified experimentally; awarded the Nobel prize in 1921 for this last accomplishment; author of the special theory of relativity in 1905 and of the general theory of relativity in 1914, both of which have had great success in explaining otherwise unexplained phenomena and in predicting new ones

JAMES CLERK MAXWELL (1831–1879)

One of the greatest of mathematical physicists; born in Edinburgh, Scotland; professor of natural philosophy at Marischal College, Aberdeen, in 1856, of physics and astronomy in King's College, London, in 1860, and of experimental physics in Cambridge University from 1871 to 1879; one of the most prominent figures in the development of the kinetic theory of gases and the mechanical theory of heat; author of the electromagnetic theory of light — a theory which has become the basis of nearly all modern theoretical work in electricity and optics (see page 469)

Again, chemists tell us that if two globes, one containing hydrogen and the other carbon dioxide gas, be connected as in Fig. 51, and the stopcock between them be opened, after a few hours chemical analysis will show that each of the globes contains the two gases in exactly the same proportions, — a result which is at first sight very surprising, since carbon dioxide gas is about twenty-two times as heavy as hydrogen. This mixing of gases in apparent violation of the laws of weight is called *diffusion*.

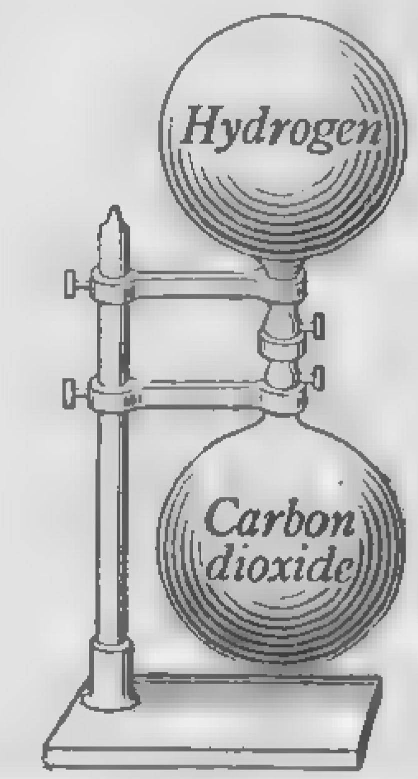


FIG. 51. Illustrating the diffusion of gases

We see, then, that such simple facts as the transference of odors and the diffusion of gases furnish very convincing evidence that the molecules of a gas are not at rest but are continually moving about.

63. **Molecular motions and the indefinite expansibility of a gas.** Perhaps the most striking property which we have found gases to possess is the property of indefinite, or unlimited, expansibility. The existence of this property was demonstrated by the fact that we were able to attain a high degree of exhaustion by means of an air pump. No matter how much air was removed from the bell jar, the remainder at once expanded and filled the entire vessel. The motions of the molecules furnish a thoroughly satisfactory explanation of the phenomenon.

The fact that, however rapidly the piston of the air pump is drawn up, gas always appears to follow it instantly, leads us to the conclusion that the natural velocity possessed by the molecules of gas must be very great.

64. **Molecular motions and gas pressures.** How are we to account for the fact that gases exert such pressures as they do against the walls of the vessels which contain them? We have found that in a room at sea level the air presses against the walls with a force of 15 pounds to the square inch. Within a pneumatic truck tire this pressure may amount to as much

as 100 pounds, and the steam pressure within the boiler of a locomotive is often as high as 240 pounds per square inch. Yet in all these cases we may be certain that the molecules of the gas are separated from each other by distances which are large in comparison with the diameters of the molecules; for when we reduce steam to water, it shrinks to $\frac{1}{1600}$ of its original volume, and when we reduce air to the liquid form, it shrinks to about $\frac{1}{800}$ of its ordinary volume.

The explanation is at once apparent when we reflect upon the *motions* of the molecules. For just as a stream of water particles from a hose exerts a continuous force against a wall on which it strikes, so the blows which the innumerable molecules of a gas strike against the walls of the containing vessel must constitute a continuous force tending to push out these walls. In this way we account for the fact that vessels containing only gas do not collapse under the enormous external pressures to which we know them to be subjected.

65. Explanation of Boyle's law. It was discovered in the last chapter that when the density of a gas is doubled, the temperature remaining constant, the pressure is likewise found to double; that when the density is trebled, the pressure is trebled; etc. This, in fact, was the assertion of Boyle's law. Now this is exactly what would be expected if the pressure which a gas exerts against a given surface is caused by blows struck by an enormous number of swiftly moving molecules; for doubling the number of molecules in the given space (that is, doubling the density) would simply double the number of blows which are struck per second against that surface, and hence would double the pressure. The kinetic theory of gases which is here presented accounts in this simple manner for Boyle's law.

66. Brownian movements and molecular motions. It has recently been found possible to demonstrate the existence of molecular motions in gases in a very direct and striking way. It is found that very minute oil drops suspended in perfectly stagnant air, instead of being themselves at rest, are ceaselessly dancing about just as though they were endowed with life. In 1913 it was definitely proved that these motions, which are known as the *Brownian movements*, are the direct result of the bombardment which the droplets receive from the flying molecules of the gas with which they are surrounded; for at a given instant this bombardment is not the same on all sides, and hence the suspended particle, if it is minute enough, is pushed hither and thither according as the bombardment is more intense first in one direction, then in another. There can be no doubt that what the oil drops are here seen to be doing, the molecules themselves are also doing, only in a much more lively way.

67. Molecular velocities. From the known weight of a cubic centimeter of air under normal conditions, and the known force which it exerts per square centimeter (namely, 1033 g.), it is possible to calculate the velocity which its molecules must possess in order that they may produce this amount of force by their collisions against the walls. The result of the calculation gives to the air molecules under normal conditions a velocity of about 445 m. per second, and it assigns to the hydrogen molecules the enormous speed of 1700 m. (over a mile) per second. The speed of a projectile is seldom greater than 800 m. (2600 ft.) per second. It is easy to see, then, since the molecules of gases are endowed with such speeds, why air, for example, expands instantly into the space left behind by the rising piston of the air pump, and why any gas always fills completely the vessel which contains it (see mercury-diffusion air pump, opposite page 35).

68. Diffusion of gases through porous walls. Strong evidence of the correctness of the views given above is furnished by the following experiment:

Let a porous cup of unglazed earthenware be closed with a rubber stopper through which a glass tube passes, as in Fig. 52. Let the tube be dipped into a dish of colored water, and a jar containing hydrogen be placed over the porous cup; or let the jar simply be held in the position shown in the figure, and illuminating gas be passed into it by means of a rubber tube connected with a gas jet. The rapid passage of bubbles out through the water will

show that the gaseous pressure inside the cup is rapidly increasing. Now let the bell jar be lifted so that the hydrogen is removed from the outside. Water will at once begin to rise in the tube, showing that the pressure within the porous cup is now rapidly decreasing.

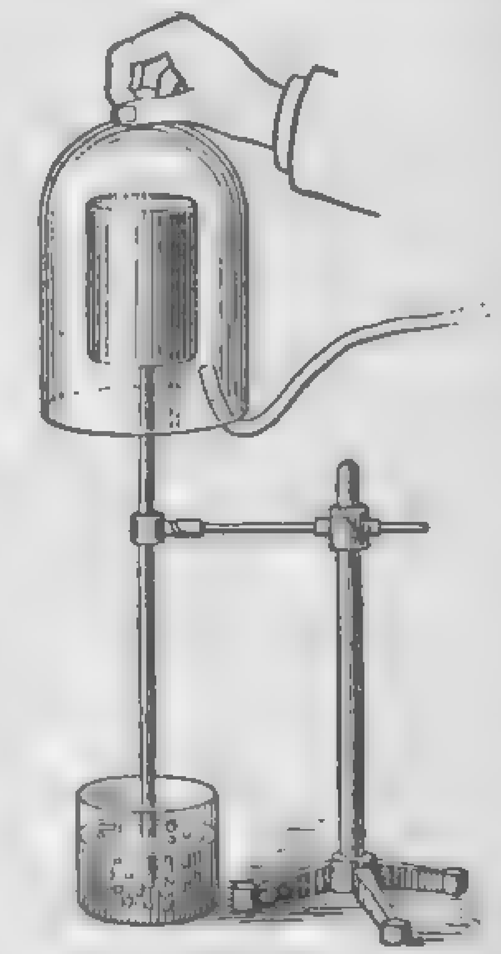


FIG. 52. Diffusion of hydrogen through a porous cup

The explanation is as follows: We have learned that the molecules of hydrogen have about four times the velocity of the molecules of air. Therefore, if there are as many hydrogen molecules per cubic centimeter outside the cup as there are air molecules per cubic centimeter inside, the hydrogen molecules will strike the outside of the wall four times as frequently as the air molecules will strike the inside. Therefore, in a given time the number of hydrogen molecules which pass into the interior of the cup through the little holes in the porous material is four times as great as the number of air particles which pass out; hence the pressure within increases. When the bell jar is removed, the hydrogen which has passed inside begins to pass out faster than the outside air passes in, and hence the inside pressure is diminished.

Molecular Motions in Liquids

69. Molecular motions in liquids and evaporation. Evidence that the molecules of liquids as well as those of gases are in a state of perpetual motion is found, first, in the familiar facts of evaporation.

We know that the molecules of a liquid in an open vessel are continually passing off into the space above, since it is only a matter of time until the liquid completely disappears and the vessel becomes dry. Now it is hard to imagine a way in which the molecules of a liquid thus pass out of the liquid into the space above, unless these molecules, while in the

liquid condition, are in motion. As soon, however, as such a motion is assumed, the facts of evaporation become perfectly intelligible. For it is to be expected that in the jostlings and collisions of rapidly moving liquid molecules an occasional molecule will acquire a velocity much greater than the average. This molecule may then, because of the unusual speed of its motion, break away from the attraction of its neighbors and fly off into the space above. This is, indeed, the mechanism by which we now believe that the process of evaporation goes on from the surface of any liquid.

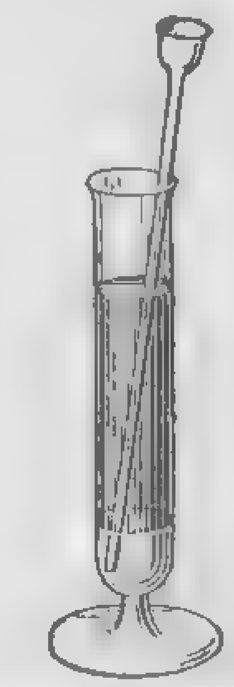


FIG. 53. Diffusion of liquids

70. Molecular motions and the diffusion of liquids. One of the most convincing arguments for the motions of molecules in gases was found in the fact of diffusion. But precisely the same sort of phenomena are observable in liquids.

Let a few lumps of blue litmus be pulverized and dissolved in water. Let a tall glass cylinder be half filled with this water and let a few drops of ammonia be added. Let the remainder of the litmus solution be turned red by the addition of one or two cubic centimeters of nitric acid. Then let this acidulated water, slightly cooled, be introduced into the bottom of the jar through a thistle tube (Fig. 53). In the course of a few hours, even though the jar is kept perfectly quiet, the red color will be found to have spread considerably toward the top, showing that the acid molecules have gradually found their way up.

Certainly, then, the molecules of a liquid must be endowed with the power of independent motion. Indeed, every one of the arguments for molecular motions in gases applies with equal force to liquids. Even the Brownian movements can be seen in liquids, though they are here so small that high-power microscopes must be used to make them visible. If a small amount of insoluble carmine is ground into a few drops of water, these movements may be seen with a microscope magnifying four hundred or more diameters.

Molecular Motions in Solids

71. Molecular motions and the diffusion of solids. It has recently been demonstrated that if a layer of lead is placed upon a layer of gold, molecules of gold may in time be detected throughout the whole mass of the lead. This diffusion of solids into one another at ordinary temperatures has been shown only for these two metals, but at higher temperatures (for example, 500° C.) all the metals show this same characteristic to a surprising degree. We know that molecules break away from the surface of certain solids; for example, gum camphor and naphthalene, as their odor may be detected at a considerable distance.

The evidence for the existence of molecular motions in solids is, then, no less strong than in the case of liquids.

72. The three states of matter. Although it has been shown that, in accordance with current belief, the molecules of all substances are in very rapid motion, yet differences exist in the kind of motion which the molecules in the three states possess. Thus, in the solid state it is probable that the molecules oscillate with great rapidity about certain fixed points, always being held by the attractions of their neighbors — that is, by the *cohesive forces* (see § 113) — in very nearly the same positions with reference to other molecules in the body. In rare instances, however, as the facts of diffusion show, a molecule breaks away from its constraints. In *liquids*, on the other hand, although the molecules are, in general, as close together as in solids, they slip about with perfect ease over one another and thus have no fixed positions. This assumption is justified by the fact that liquids adjust themselves readily to the shape of the containing vessel. In *gases* the molecules are comparatively far apart, as is evident from the fact that a cubic centimeter of water occupies about 1600 cubic centimeters when it is transformed into steam; and, furthermore, they exert almost no cohesive force upon one another, as is shown by the indefinite expansibility of gases.

Summary. The theory of the molecular constitution of matter is now universally accepted.

Evidence of molecular motion (the kinetic theory of matter) is found in diffusion, in indefinite expansibility of gases, in Brownian movements, and in the evaporation of liquids and solids.

Boyle's law is explained by the assumption that at a given temperature the pressure is determined by the number of molecular blows per second on unit area.

The rate of diffusion of a light gas is greater than that of a heavy one because of the greater velocity of its less massive molecules.

QUESTIONS AND PROBLEMS*

1. Account for the fact that if ammonia water is spilled in a room, the odor of the ammonia gas may be quickly detected in all parts of the room.

2. Why does not the tendency to unlimited expansion cause the atmosphere to leave the earth?

3. Why does a confined body of gas exert pressure inversely proportional to its volume?

4. A lump of copper sulphate placed at the bottom of a graduate filled with water will dissolve and very slowly pass upward, although a copper-sulphate molecule is many times heavier than a water molecule. Explain.

5. What is the density of the air within an automobile tire that is inflated to a *gauge* pressure of 30 lb. per square inch? (Take 1 atmosphere = 15 lb. per square inch.)

6. A liter of air at a pressure of 76 cm. is compressed so as to occupy 400 cc. What is the pressure against the walls of the containing vessel?

7. Salt is heavier than water. Why does not all the salt in a mixture of salt and water settle to the bottom?

* Supplementary questions and problems for Chapter IV are given in the Appendix.

CHAPTER V

FORCE AND MOTION

Definition and Measurement of Force

X

73. Distinction between a gram of mass and a gram of force. If a gram of mass is held in the outstretched hand, a downward pull upon the hand is felt. If the mass is 50,000 grams instead of 1, this pull is so great that the hand cannot be held in place. The cause of this pull we assume to be an attractive force which the earth exerts on the matter held in the hand, and *we define the gram of force as the amount of the earth's pull at its surface upon 1 gram of mass.*

Unfortunately, in ordinary conversation we often fail altogether to distinguish between the idea of mass and that of force, and we use the same word "gram" to mean sometimes *a certain amount of matter* and at other times *the pull of the earth upon this amount of matter.* That the two ideas are wholly distinct, however, is evident from the consideration that the amount of matter in a body is always the same, wherever the body is in the universe, whereas the pull of the earth upon that amount of matter decreases as we recede from the earth's surface. It will help to avoid confusion if we reserve the simple term "gram" to denote exclusively an amount of matter (that is, a mass) and use the full expression "gram of force" wherever we have in mind the pull of the earth upon this mass.

74. Method of measuring forces. When we wish to compare accurately the pulls exerted by the earth upon different masses, we find the muscular sense a very untrustworthy guide. An accurate method, however, of comparing these pulls is that furnished by the stretch produced in a spiral

spring. Thus, the pull of the earth upon a gram of mass at its surface will stretch a given spring a given distance, *ab* (Fig. 54); the pull of the earth upon 2 grams of mass is found to stretch the spring a larger distance, *ac*; upon 3 grams, a still larger distance, *ad*; and so on. In order to graduate a spring balance (Fig. 55) so that it will thenceforth measure the values of any pulls exerted upon it, no matter how these pulls may arise, we have only to place a fixed surface behind the pointer and make lines upon it corresponding to the points to which it is stretched by the pull of the earth upon different masses. For example, if a man stretches the spring so that the pointer is opposite the mark corresponding to the pull of the earth upon 2 grams of mass, we say that he exerts 2 grams of force; if he stretches it the distance corresponding to the pull of the earth upon 3 grams of mass, he exerts 3 grams of force; and so on. *The spring balance thus becomes an instrument for measuring forces.*

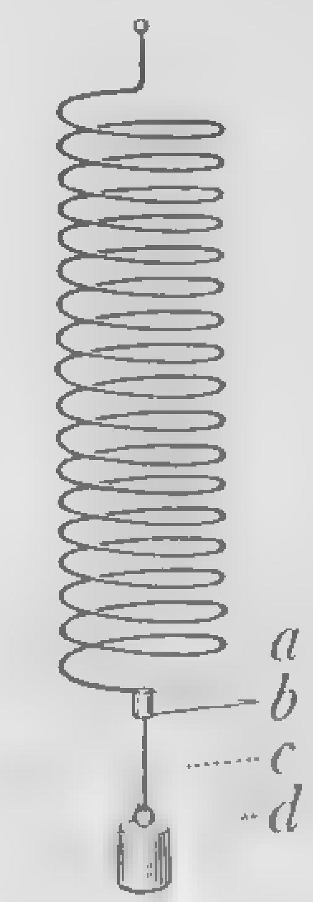


FIG. 54. Method of measuring forces

75. The gram of force varies slightly in different localities. With the spring balance it is easy to verify the statement made above, that the force of the earth's pull decreases as we recede from the earth's surface; for upon a high mountain the stretch produced by the weight of a given mass is, indeed, found to be slightly less than at sea level. Furthermore, if the balance is simply carried from point to point over the earth's surface, the stretch is still found to vary slightly. For example, at Chicago it is about one part in 1000 less than it is at Paris, and near the equator it is five parts in 1000 less than it is near the pole. This is due in part to the earth's rotation and in part to the fact that the

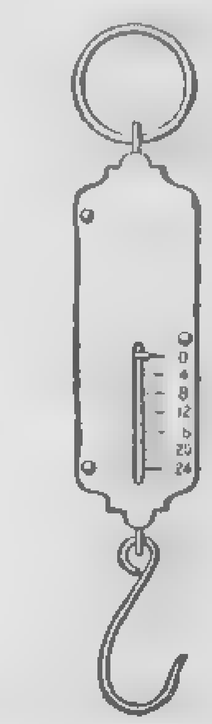


FIG. 55. The spring balance

earth is not a perfect sphere and that in going from the equator toward the pole we are coming nearer and nearer to the center of the earth. We see, therefore, that *the weight of 1 gram of mass is not an absolutely definite unit of force.*

Composition and Resolution of Forces*

76. Graphic representation of force. A force is completely described when its *magnitude,* its *direction,* and the *point at which it is applied* are given. Since the three characteristics of a straight line are its *length,* its *direction,* and the *point at which it starts,* it is obviously possible to represent forces by means of straight lines. Thus, if we wish to represent the fact that a force of 8 pounds, acting in an easterly direction, is applied at the point A (Fig. 56), we draw a line 8 units long, beginning at the point A and extending to the right. The length, the direction, and the starting point of this line represent the magnitude, the direction, and the point of application, respectively, of the force.

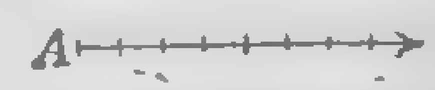


FIG. 56. Graphic representation of a single force

77. Resultant of two forces acting in the same line. *The resultant of two forces is defined as that single force which will produce the same effect upon a body as is produced by the joint action of the two forces.*

If two spring balances are attached to a small ring and pulled in the same direction until one registers 10 grams of force and the other 5, it will be found that a third spring balance attached to the same point and pulled in the opposite direction will register exactly 15 grams when there is equilibrium; that is, *the resultant of two parallel forces acting in the same direction is equal to the sum of the two forces.*

Similarly, *the resultant of two oppositely directed forces applied at the same point is equal to the difference between them, and its direction is that of the greater force.*

*Laboratory experiments on parallel and concurrent forces should accompany this discussion. See, for example, Experiments 10 and 11 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

78. Equilibrant. In the last experiment the pull in the spring balance which registered 15 grams was not the resultant of the 5-gram and 10-gram forces: it was rather a force equal and opposite to that resultant. Such a force is called an *equilibrant. The equilibrant of a force or forces is that single force which will just balance these forces; that is, prevent the motion which the given forces tend to produce.* It is equal and opposite to the resultant and has the same point of application.

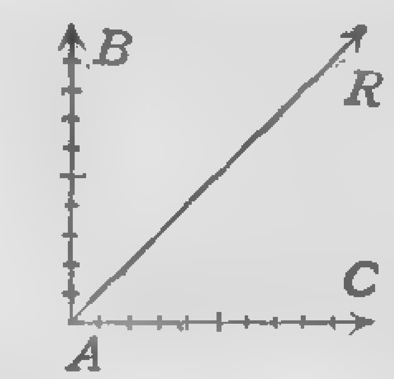


FIG. 57. Direction of resultant of two equal forces at right angles

79. Resultant of forces acting at an angle (concurrent forces). If a body placed at A is pulled toward the east with a force of 10 pounds (represented in Fig. 57 by the line AC) and toward the north with a force of 10 pounds (represented in the figure by the line AB), the effect upon the motion of the body must, of course, be the same as though some single force acted somewhere between AC and AB. If the body *moves* under the action of the two equal forces, it may be seen from symmetry that it must move along a line midway between AC and AB; that is, along the line AR. Therefore this line indicates the *direction* as well as the point of application of the resultant of the forces AC and AB.

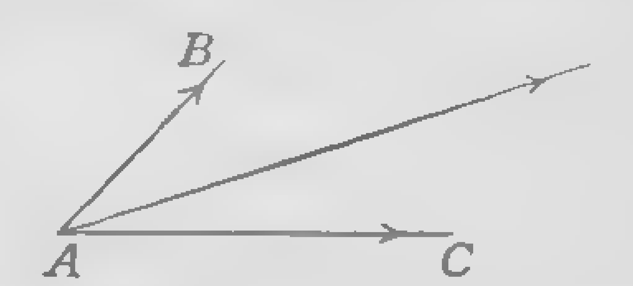


FIG. 58. The resultant lies nearer the larger force

If the two forces are not equal, as in Fig. 58, then the resultant will lie nearer the larger force. The following experiment will show the relation between the two forces and their resultant.

Let the rings of two spring balances be hung over nails B and C in the rail at the top of the blackboard (Fig. 59), and let a weight W be tied near the middle of the string joining the hooks of the two balances. The weight W is not supported by the pull of the balance E or by that of F; it is supported by their resultant, which evidently must act vertically upward, since the only *single*

force capable of supporting the weight W is one that is equal and opposite to W. Let the lines OA and OD be drawn upon the blackboard behind the string, and upon these lines lay off the distances Oa and Ob, which contain as many units of length as there are units of force indicated by the balances E and F respectively. Similarly, on a vertical line from O lay off the exact distance OR required to represent the force that supports the weight. This, as noted above, represents the resultant. Now let a parallelogram be constructed upon Oa and Ob as sides. The line OR already drawn will be found to be the diagonal.

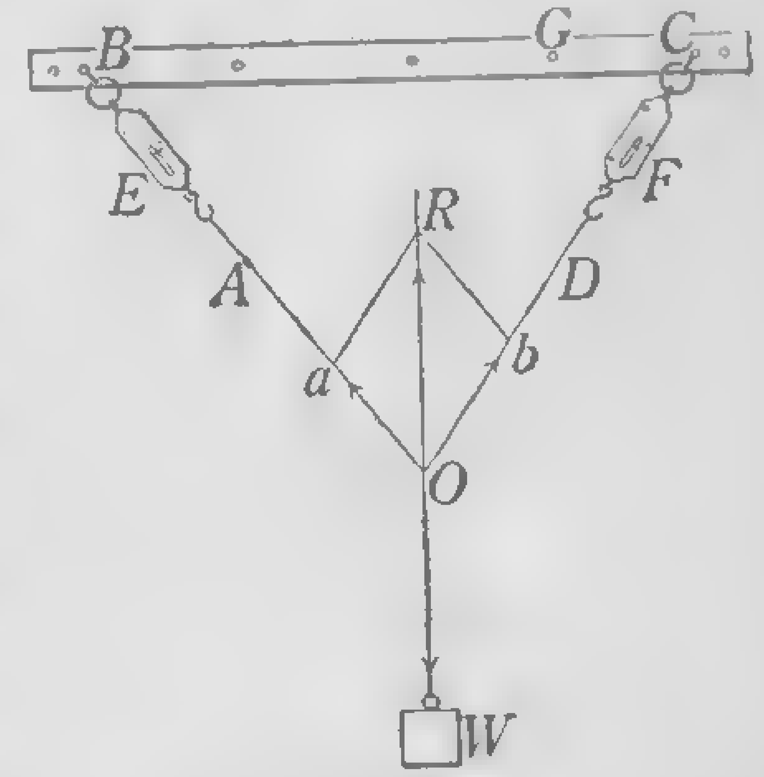


FIG. 59. Experimental proof of parallelogram law

Hence, *to find graphically the resultant of two concurrent forces,* (1) *represent the concurrent forces,* (2) *construct upon them as sides a parallelogram, and* (3) *draw a diagonal from the point of application. This diagonal represents the point of application, the direction, and the magnitude of the resultant.*

80. Component of a force. Whenever a force acts upon a body in some direction other than that in which the body is free to move, it is clear that the full effect of the force cannot be spent in producing motion. For example, suppose that a force is applied in the direction OR (Fig. 60) to a car on an elevated track. Evidently OR produces two distinct effects upon the car: on the one hand, it moves the car along the track; on the other, it presses it down against the rails. These two effects might be produced just as well by two separate forces acting in the directions OA and OB respectively. The value of the single force which, acting in the direction OA, will produce the same motion of the car on the track as is produced by OR is called the *component* of OR in the direction OA. Similarly, the value of the single force which, acting in the direction OB, will produce the same pressure against the rails as is produced by the force OR is called the component of OR in the direction OB. In a word, *the component of a force in a given direction is the effective value of the force in that direction.*

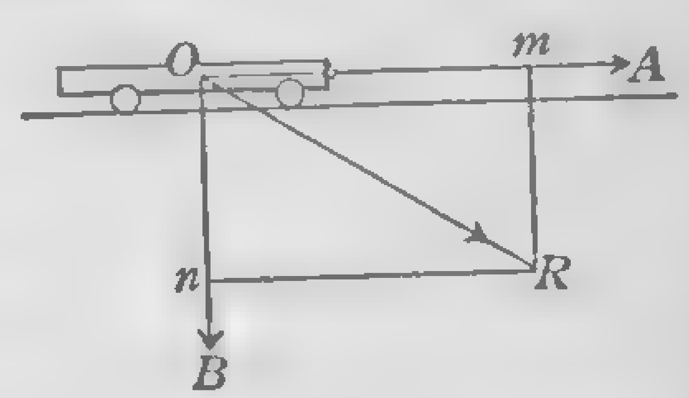


FIG. 60. Component of a force

81. Magnitude of the component of a force in a given direction. Since, from the definition of "component" just given, the two forces, one to be applied in the direction OA and the other in the direction OB, are together to be exactly equivalent to OR in their effect on the car, their magnitudes must be represented by the sides of a parallelogram of which OR is the diagonal. For in § 79 it was shown that if any one force is to have the same effect upon a body as two forces acting simultaneously, it must be represented by the diagonal of a parallelogram the sides of which represent the two forces. Hence, conversely, if two forces are to be equivalent in their joint effect to a single force, they must be represented by the sides of the parallelogram of which the diagonal represents the single force. Hence the following rule: *To find the component of a force in any given direction, represent the force by a line; then, using the line as a diagonal, construct upon it a parallelogram the sides of which are, respectively, parallel and perpendicular to the direction of the required component. The length of the side which is parallel to the given direction represents the magnitude of the component which is sought.* Thus, in Fig. 60 the line Om completely represents the component of OR in the direction OA, and the line On represents the component of OR in the direction OB.

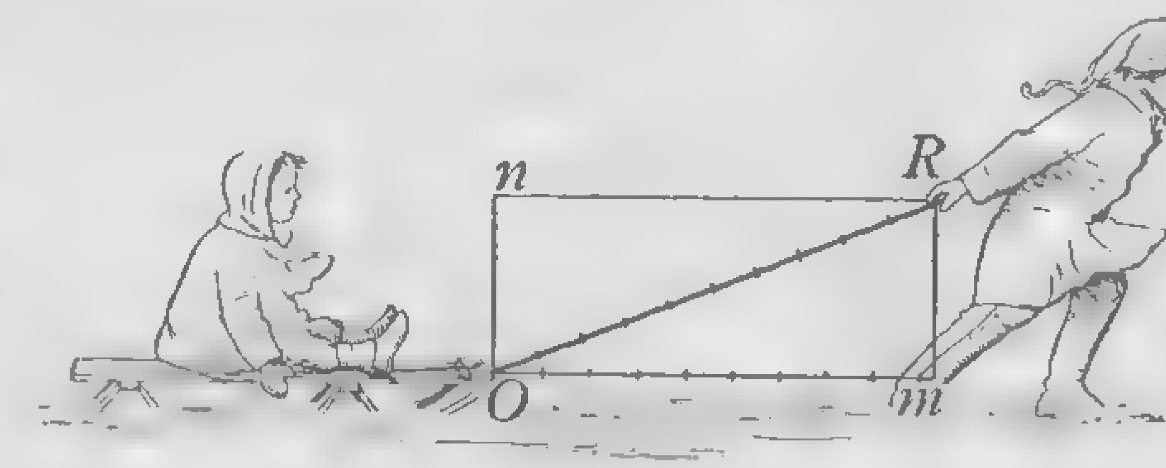


FIG. 61. Horizontal component of pull on a sled

Again, when a boy pulls on a sled with a force of 10 pounds in the direction OR (Fig. 61), the force with which the sled is

urged forward is represented by the length of *Om*, which is seen to be but 9.3 pounds instead of 10 pounds. The component which tends to lift the sled is represented by *On*.

To apply the test of experiment to the conclusions of the preceding paragraph, let a wagon be placed upon an inclined plane (Fig. 62) the height of which, *bc*, is equal to half its length *ab*. In this case the force acting on the wagon is the weight of the wagon, and its direction is downward. Let this force be represented by the line *OR*. Then, by the construction of the preceding paragraph, the line *Om* will represent the value of the force which is pulling the carriage down the plane, and the line *On* the value of the force which is producing pressure against the plane. Now, since the triangle *ROm* is similar to the triangle *abc* (for $\angle mOR = \angle abc$, $\angle RmO = \angle acb$, and $\angle ORm = \angle bac$), we have

$$\frac{Om}{OR} = \frac{bc}{ab};$$

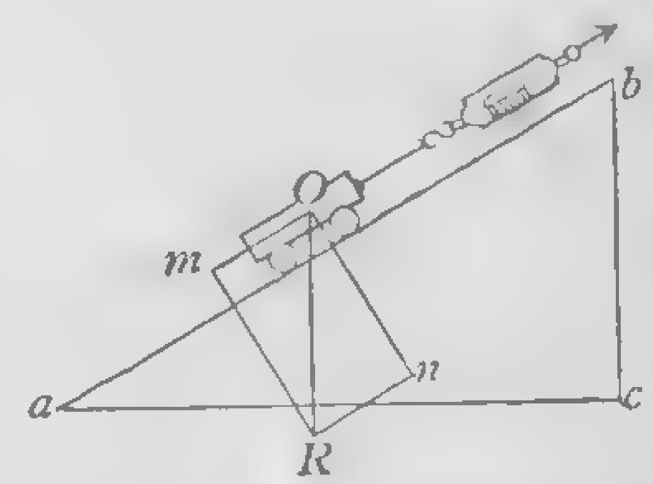


FIG. 62. Component of weight parallel to an inclined plane

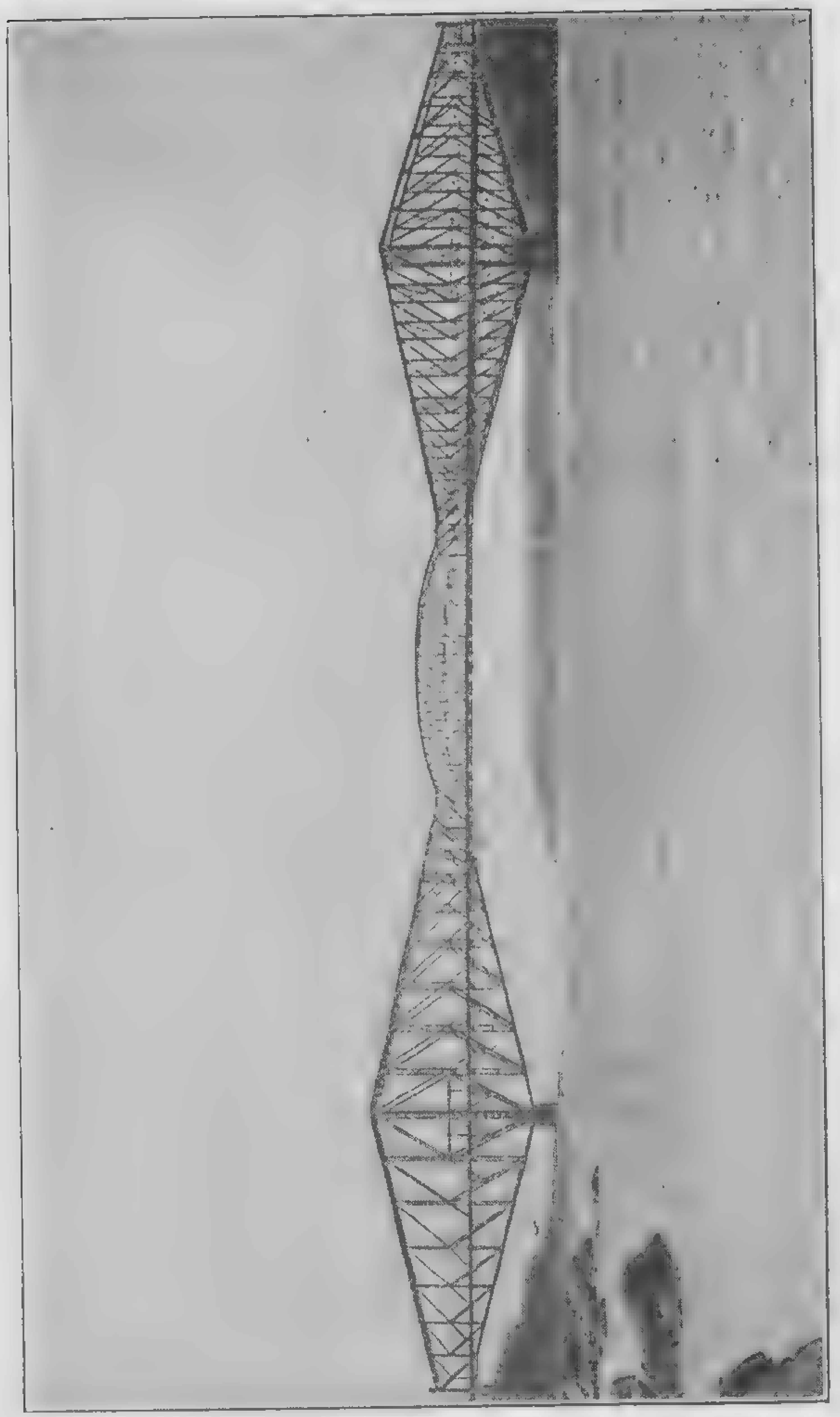
that is, in this case, since *bc* is equal to half of *ab*, *Om* is half of *OR*. Therefore the force which is necessary to prevent the wagon from running down the plane should be equal to half its weight. To test this conclusion let the wagon be weighed on the spring balance and then placed on the plane in the manner shown in the figure. The pull indicated by the balance will, indeed, be found to be half the weight of the wagon, if there is little or no friction.

The equation $Om/OR = bc/ab$ gives us the following rule for finding the force necessary to prevent a body from moving down an inclined plane: *The force which must be applied to a body to hold it in place upon an inclined plane bears the same ratio to the weight of the body as the height of the plane bears to its length.*

82. Component of gravity effective in producing the motion of the pendulum. When a pendulum is drawn aside from its position of rest (Fig. 63), the force acting on the bob is its weight, and the direction of this force is vertical. Let the force be represented by the line *OR*. The component of this force in the direction in which the bob is free to move is

SIR ISAAC NEWTON (1642–1727)

English mathematician and physicist; "prince of philosophers"; professor of mathematics at Cambridge University; formulated the law of gravitation; discovered the binomial theorem; invented the method of the calculus; announced the three laws of motion which have become the basis of the science of mechanics; made important discoveries in light; is the author of the celebrated "Principia" (Principles of Natural Philosophy), published in 1687



THE GREAT CANTILEVER BRIDGE AT QUEBEC

The channel span of this bridge measures 1800 feet. It is the longest cantilever bridge in the world, being 90 feet longer than the famous Forth Bridge in Scotland. The central suspended span is 640 feet long and weighs 5600 tons. The cost of the bridge was nearly $17,000,000. About 3,000,000 rivets were used to hold together the pieces of steel

On (or *On'*), and the component at right angles to this direction is *Om* (or *Om'*). The second component simply produces stretch in the string and pressure upon the point of suspension. The first component is alone responsible for the motion of the bob. A consideration of the figure shows that this component becomes larger and larger the greater the displacement of the bob. When the bob is directly beneath the point of support, the component producing motion is zero. Hence a pendulum can be permanently at rest only when its bob is directly beneath the point of suspension.*

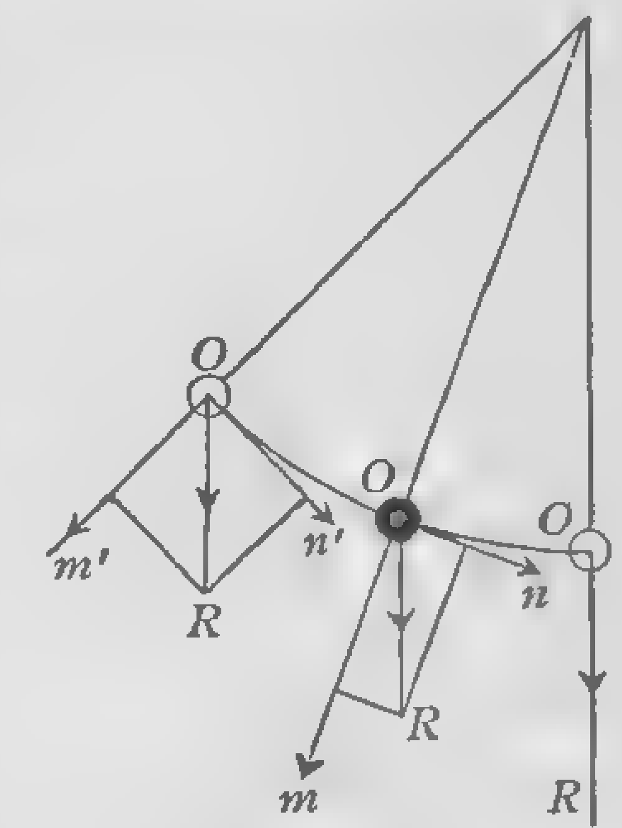


FIG. 63. Force acting on displaced pendulum

83. Laws of the pendulum. The laws of the pendulum are obtained from the following experiments:

Let two pendulums of exactly the same length (about 1 m.), one having a bob of lead and the other a bob of steel or glass, be pulled back and released at the same instant, and their periods observed. We shall thus obtain the first law of the pendulum; namely,

1. *The periods of pendulums of the same length swinging through short arcs are independent of the mass and the material of the bobs.*

Let the two pendulums be set swinging through arcs of lengths 2 cm. and 5 cm. respectively. We shall thus find the second law of the pendulum; namely,

2. *The period of a pendulum swinging through a short arc is independent of the amplitude of the arc.*

Let pendulums one fourth and one ninth as long as the one used before be swung with it. The long pendulum will be found

* It is recommended that the study of the laws of the pendulum be introduced into the laboratory work at about this point (see Experiment 12 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis).

to make only one vibration while the others are making two and three respectively. Therefore the third law of the pendulum is

3. *The periods of pendulums are directly proportional to the square roots of their lengths.*

SUMMARY. A gram of mass is a definite quantity of matter which is the same everywhere; whereas a gram of force, which is the pull of the earth at sea level upon a gram of mass, varies slightly with position on the earth.

The resultant of a set of forces is that single force which will produce the same effect upon a body as is produced by the joint action of the set of forces. The rules for finding the resultant have been found (§§ 77–79).

The component of a force in a given direction is the effective value of the force in that direction. Rules for finding the component have been found (§ 81).

A pendulum swings because of the component of its weight in the direction of its motion.

The length law of the pendulum expressed as a formula is

$$\frac{t_1}{t_2} = \frac{\sqrt{l_1}}{\sqrt{l_2}}.$$

QUESTIONS AND PROBLEMS

1. A boy can row a boat 5 mi. per hour in still water. In a river which flows 2 mi. per hour, how fast would his boat move downstream? upstream?

2. The wind drives a steamer east with a force which would carry it 12 mi. per hour, and its propeller is driving it south with a force which would carry it 15 mi. per hour. What distance will it actually travel in an hour? Draw a diagram to represent the exact path.

3. Represent graphically a force of 30 lb. acting southeast and a force of 40 lb. acting southwest at the same point. What will be the magnitude of the resultant? What will be its approximate direction?

4. An airplane which flies in still air with a velocity of 120 mi. per hour is flying in a wind whose velocity is 60 mi. per hour

toward the east. Find the actual velocity of the airplane and the direction of its motion when headed north; east; south; west.

5. A barge is anchored in a river during a storm. If the wind acts eastward on it with a force of 3000 lb. and the tide acts northward on it with a force of 4000 lb., what is the direction and the magnitude of the equilibrant (that is, the pull of the anchor cable upon the barge)?

6. A cord 10 ft. long has its ends fastened 8 ft. apart on a ceiling and supports a weight of 20 lb. from its middle point. Find the tension (pull) on each of the halves of the cord.

7. A horizontal pull of 24 lb. draws a loaded sled on level snow. If the sled rope is 5 ft. long, how much pull on the rope is required to draw the sled when one end of the rope is (1) 3 ft. higher than the other; (2) 4 ft. higher than the other?

8. A canal boat and the engine towing it move in parallel paths which are 50 ft. apart. The tow rope is 130 ft. long, and the force (effort) applied to the end of the rope is 1300 lb. Find what component of the 1300 lb. acts parallel to the path of the boat.

9. A child weighing 100 lb. sits in a swing. The swing is drawn aside and held in equilibrium by a horizontal force of 40 lb. Find the tension on each of the two ropes of the swing.

10. A picture weighing 20 lb. hangs upon a cord whose parts make an angle of 120° with each other. Find the tension on each part of the cord.

11. If the parts of the cord in Problem 10 had made an angle of 90°, what would have been the tension on each part of the cord?

12. Three boys, weighing each 100 lb., hang from a horizontal ladder as shown in Fig. 64: (1) arms parallel; (2) arms at 90°; (3) arms at 120°. Find in each case how much the arms pull to support the weight of the boy.

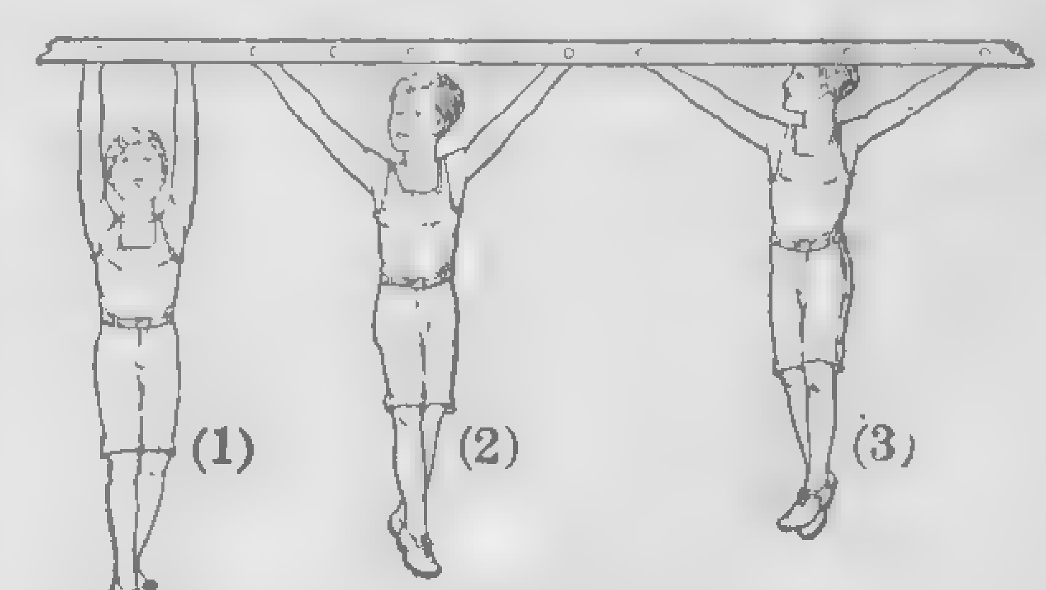


FIG. 64

13. The anchor rope of a kite balloon makes an angle of 60° with the surface of the earth. If the lifting force of the balloon is 1000 lb., find the pull of the balloon on the rope, and the horizontal force of the wind against the balloon.

14. If the barrel of Fig. 65 weighs 200 lb., with what force must a man push parallel to the skid and through the center of the barrel to keep the barrel in place if the skid is 9 ft. long and the platform 3 ft. high?

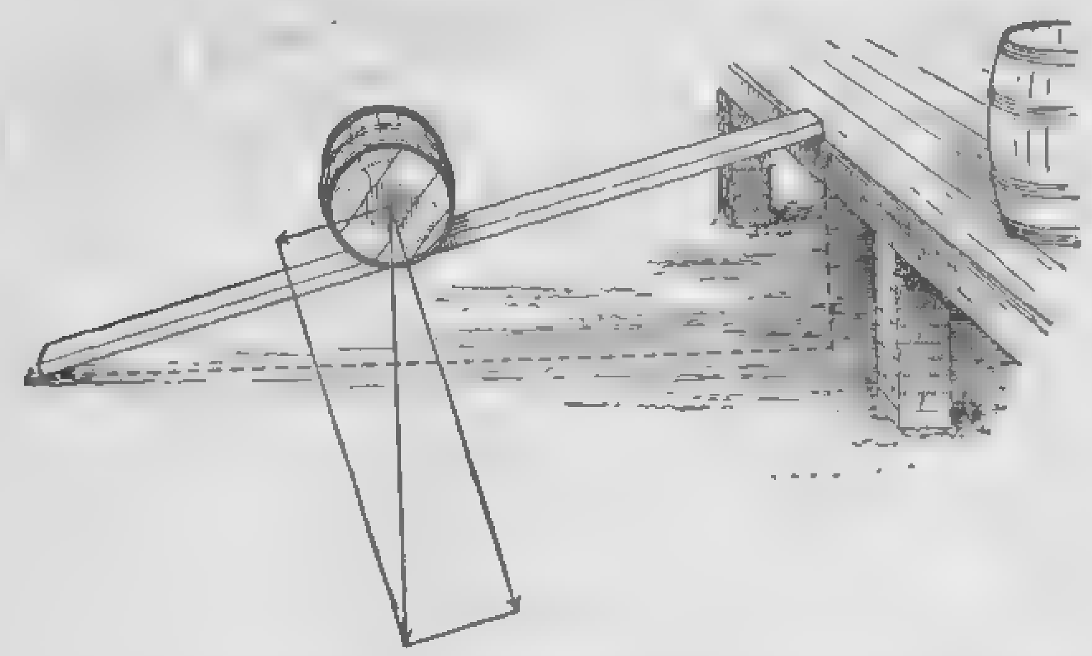


FIG. 65. Force necessary to prevent a barrel from rolling down an inclined plane

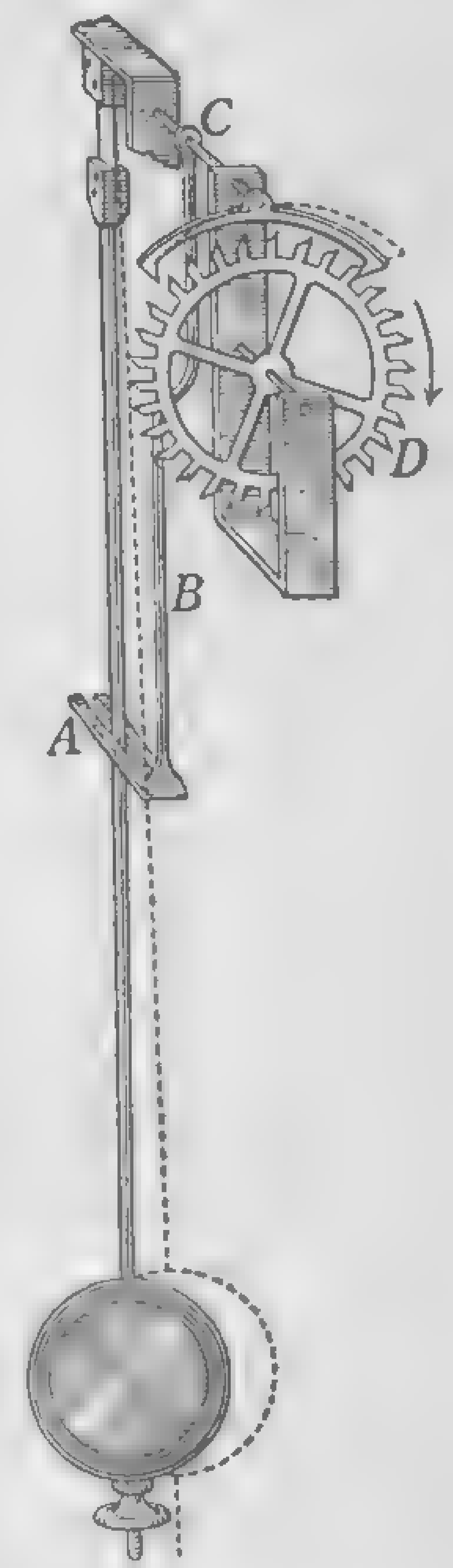


FIG. 66

15. A pendulum that makes a single swing per second in New York City is 99.3 cm., or 39.1 in., long. Account for the fact that a seconds pendulum at the equator is 39 in. long, whereas at the poles it is 39.2 in. long.

16. How long is a pendulum whose period is 3 sec.? 2 sec.? $\frac{1}{2}$ sec.? $\frac{1}{3}$ sec.?

17. Fig. 66 represents the pendulum and escapement of a clock. The escapement wheel D is urged in the direction of the arrow by the clock weights or spring. The slight pushes communicated by the teeth of the wheel keep the pendulum from dying down. Show how the length of the pendulum controls the rate of the clock.

18. The lengths of 5 pendulums are in the ratio of $1:4:9:\frac{1}{4}:\frac{1}{9}$. What is the ratio of their periods?

GRAVITATION

84. Newton's law of universal gravitation. In order to account for the fact that the earth pulls bodies toward itself, and also that the moon and the planets are held in their re-

spective orbits about the earth and the sun, Sir Isaac Newton (1642–1727) (see opposite page 68) first announced the law which is now known as the law of universal gravitation. This law asserts first that *every body in the universe attracts every other body with a force which varies inversely as the square of the distance between the two bodies.* This means that if the distance between the two bodies considered is doubled, the force will become only one fourth as great; if the distance is made three, four, or five times as great, the force will be reduced to one ninth, one sixteenth, or one twenty-fifth of its original value; etc.

The law further asserts that if the distance between two bodies remains the same, *the force with which one body attracts the other is proportional to the product of the masses of the two bodies.* Thus we know that the earth attracts 3 cubic centimeters of water with three times as much force as it attracts 1; that is, with a force of 3 grams. We know also, from the facts of astronomy, that if the mass of the earth were doubled, its diameter remaining the same, it would attract 3 cubic centimeters of water with twice as much force as it does at present; that is, with a force of 6 grams (multiplying the mass of one of the attracting bodies by 3 and that of the other body by 2 multiplies the forces of attraction by 3×2, or 6). In brief, then, Newton's law of universal gravitation is as follows: *Any two bodies in the universe attract each other with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.*

Two masses of 1 gram each at a distance apart of 1 centimeter attract each other with a force of approximately $\frac{1}{15,000,000,000}$ gram. The masses of the sun and the earth are so great that even though 93,000,000 miles apart, they attract each other with a force of about 4,000,000,000,000,000,000 tons. A solid bar of high-grade steel 93,000,000 miles long and 5000 miles in diameter would be needed to replace gravitation in holding the earth and the sun together. A body

weighing 100 pounds on the earth would weigh about 2700 pounds on the sun. A freely falling body on the earth drops 16 feet the first second; on the sun it would fall 27 times as far in the first second, or 432 feet. On the moon we should weigh $\frac{1}{6}$ of what we do on the earth; we could jump 6 times as high and should fall $\frac{1}{6}$ as fast.

85. Variation of the force of gravity with distance above the earth's surface. If a body is spherical in shape and of uniform density, it attracts external bodies with the same force as though its mass were concentrated at its center. Since, therefore, the distance from the surface to the center of the earth is about 4000 miles, we learn from Newton's law that the earth's pull upon a body 4000 miles above its surface is but one fourth as much as it would be at the surface.

It will be seen, then, that if a body is raised a few feet or even a few miles above the earth's surface, the decrease in its weight must be a very small quantity, for the reason that a few feet or a few miles is a small distance compared with 4000 miles. As a matter of fact, at the top of a mountain 4 miles high 1000 grams of mass is attracted by the earth with 998 grams of force instead of 1000 grams.

86. Center of gravity. From the law of universal gravitation it follows that every particle of a body upon the earth's surface is pulled toward the earth. It is evident that the sum of all these little pulls on the particles of which the body is composed must be equal to the total pull of the earth upon the body. Now it is always possible to find one single point in a body at which a single force, equal in magnitude to the weight of the body and directed upward, can be applied so that the body will remain at rest (that is, be balanced) in whatever position it is placed. This point is called the *center of gravity* of the body. Since this force counteracts entirely the earth's pull upon the body, it must be equal and opposite to the resultant of all the small forces which gravity is exerting upon the different particles of the body. Hence the center of gravity may be defined as *the point of application of the resultant of all the little downward forces of gravity acting upon the parts of the body*; that is, *the center of gravity of a body is the point at which the entire weight of the body may be considered as concentrated.* The earth's attraction for a body is therefore always considered not as a multitude of little forces but as one single force F (Fig. 67) equal to the pull of gravity upon the body and applied at its center of gravity G. It is evident, then, that *under the influence of the earth's pull, every body tends to assume the position in which its center of gravity is as low as possible.*

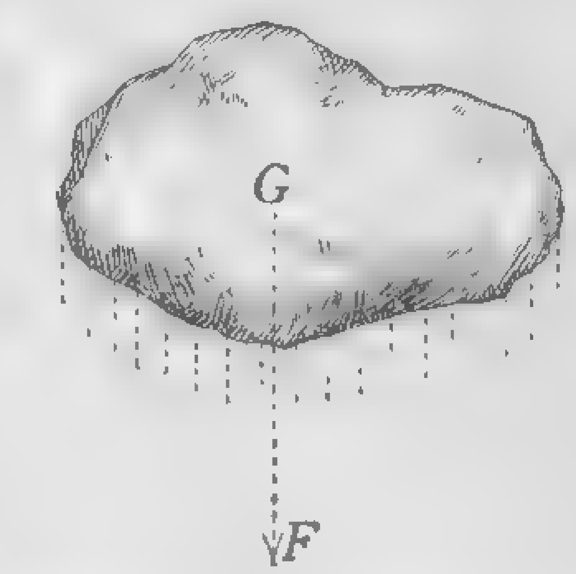


FIG. 67. Center of gravity of an irregular body

87. Method of finding center of gravity experimentally. From the preceding definition it will be seen that the most direct way of finding the center of gravity of any flat body, like that shown in Fig. 68, is to find the point upon which it will balance.

Let an irregular sheet of zinc be thus balanced on the point of a pencil or the head of a pin. Let a small hole be punched through the zinc at the point of balance, and let a needle be thrust through this hole. When the needle is held horizontally, the zinc will be found to remain at rest, no matter in what position it is turned.

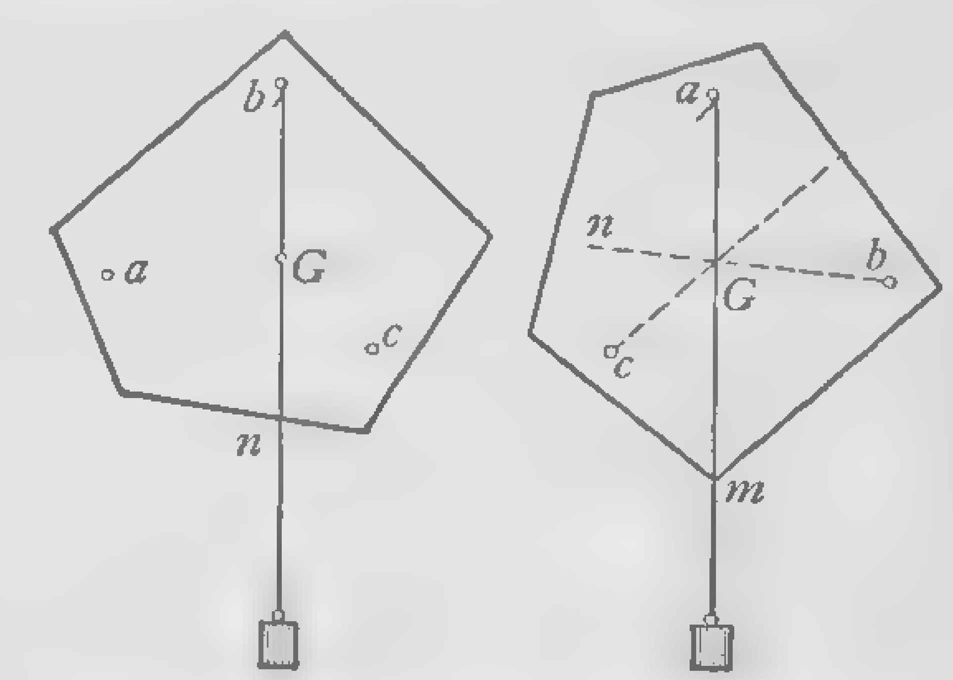


FIG. 68. Locating center of gravity

To illustrate another means of finding the center of gravity of the zinc, let it be supported by a pin stuck through a hole near its edge; for example, at b (Fig. 68). Let a plumb line be hung from the pin, and let a line bn be drawn through b on the surface of the zinc parallel to and directly behind the plumb line. Let the zinc be hung from another point, a, and let another line, am, be drawn in a similar way. The zinc will be found to balance upon the point of intersection of the lines bn and am.

Since the attraction of the earth for a body may be considered as a single force applied at the center of gravity, a suspended body (for example, the sheet of zinc) can remain at rest only when the center of gravity is directly beneath the point of support (see § 86). It must therefore lie somewhere on the line *am*. For the same reason it must lie on the line *bn*. But the only point of the body which lies on both these lines is that at their point of intersection *G*. *The point of intersection, then, of any two vertical lines dropped through two different points of suspension locates the center of gravity of a body.*

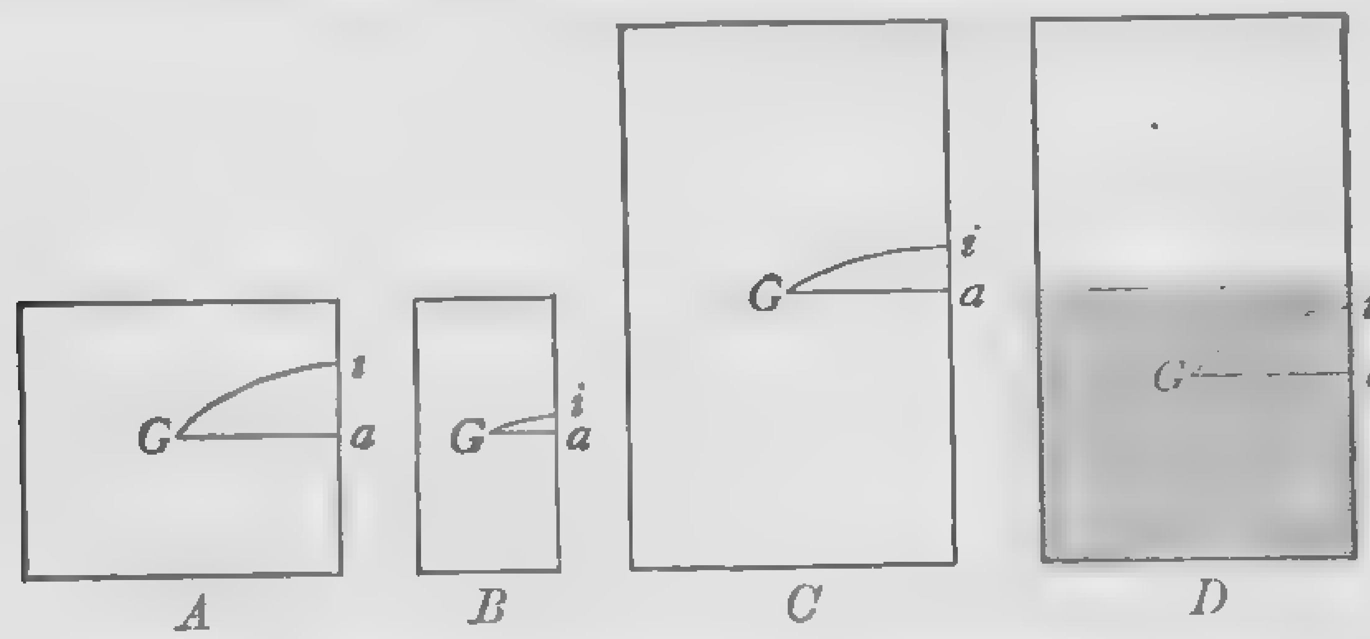


FIG. 69. Illustration of varying degrees of stability

88. Stable equilibrium. A body is said to be in *stable equilibrium* if it tends to return to its original position when it is very slightly tipped, or rotated, out of that position. A pendulum, a chair, a cube resting on its side, a cone resting on its base, and a boat floating quietly in still water are all illustrations.

In general, *a body is in stable equilibrium whenever slightly tipping it tends to raise its center of gravity.* Thus, in Fig. 69 all the bodies *A, B, C, D,* are in stable equilibrium; for in order to overturn any one of them its center of gravity *G* must be raised through the height *ai*. If the weights are equal, that one will be most stable for which *ai* is greatest. If the heights *ai* are equal, that one is most stable which has the greatest weight.

In building cantilever bridges such as the large one over the St. Lawrence River at Quebec (see opposite page 69), the engineers build out the cantilever arms equally in opposite directions, so as to keep their centers of gravity constantly over the piers until the parts either meet at the center or are close enough to receive the central span, which is hoisted to place.

The condition of stable equilibrium for bodies which rest upon a horizontal plane is that a vertical line through the center of gravity shall fall within the base, the base being defined as the polygon formed by connecting the points at which the body touches the plane, as *ABC* (Fig. 70); for it is clear that in such a case a slight displacement must serve to raise the center of gravity along the arc of which *OG* is the radius. If the vertical line drawn through the center of gravity falls outside the base, as in Fig. 71, the body must always fall; that is, the center of gravity must descend.

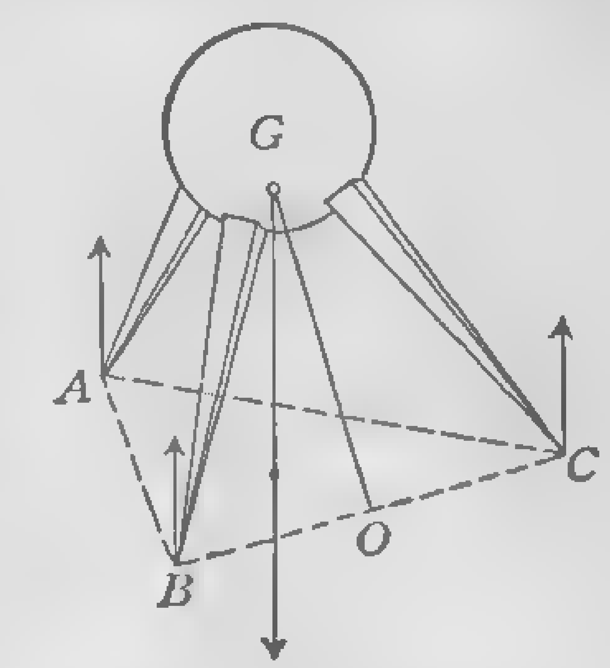


FIG. 70. Body in stable equilibrium

The condition of stable equilibrium for bodies supported from a single point, as in the case of a pendulum, is that the point of support shall be above the center of gravity. For example, the beam of a balance cannot be in stable equilibrium, so that it will return to the horizontal position when slightly displaced, unless its center of gravity *g* (Fig. 5, p. 6) is below the knife-edge *C*. (The pans are not to be considered, since they are not rigidly connected to the beam.)

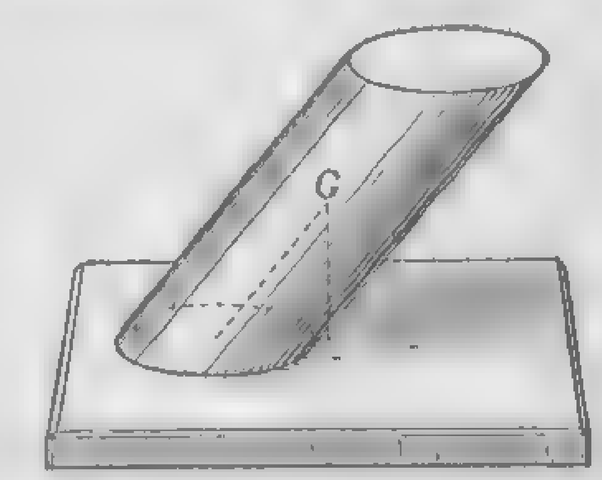


FIG. 71. Body not in equilibrium

89. Neutral and unstable equilibrium. A body is said to be in *neutral equilibrium* when, after a slight rotation, it tends neither to return to its original position nor to move farther from it. Examples of neutral equilibrium are a spherical ball lying on a smooth plane, a cone lying on its side, a wheel free to rotate about a fixed axis through its center, or any body supported at its center of gravity. In general, *a body is in neutral equilibrium when a slight rotation neither raises nor lowers its center of gravity.*

A body is in *unstable equilibrium* when, after a slight tipping, it tends to move farther from its original position. A cone balanced on its point or an egg balanced on its end are examples. In general, *a body is in unstable equilibrium when a slight tipping lowers the center of gravity.* The motion then continues until the center of gravity is as low as circumstances will permit. The condition for unstable equilibrium in the case of a body supported by a point is that the center of gravity shall be above the point of support.

SUMMARY. *Newton's law of universal gravitation.* Any two bodies in the universe attract each other with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

The center of gravity of a body is the point of application of the resultant of all the downward forces of gravity acting upon the parts of the body, or the point at which the entire weight of the body may be considered as concentrated.

A body is in equilibrium when the resultant of all the forces acting upon it is zero.

A body is in stable equilibrium whenever slightly tipping it tends to raise the center of gravity.

A body is in neutral equilibrium when a slight rotation neither raises nor lowers its center of gravity.

A body is in unstable equilibrium when a slight tipping lowers the center of gravity.

X

QUESTIONS AND PROBLEMS

1. (1) Distinguish between mass and weight. (2) Could the fact that the weight of a body changes if it is taken from the equatorial to the polar region of the earth be shown by either a spring balance or a beam balance? Explain.

2. Do you get more sugar to the pound in Panama than in New York when using a beam balance? when using a spring balance? Explain.

3. What change would there be in your weight if your mass were to become four times as great and that of the earth three times as great, the radius of the earth remaining the same?

4. The pull of the earth on a body at its surface is 100 kg. Find the pull on the same body 4000 mi. above the surface; 1000 mi. above the surface; 3 mi. above the surface. (Take the earth's radius as 4000 mi.)

5. If a lead pencil is balanced on its point on the finger, it will be in unstable equilibrium; but if two knives are stuck into it, as in Fig. 72, it will be in stable equilibrium. Why?

6. What is the object of ballast in a ship?

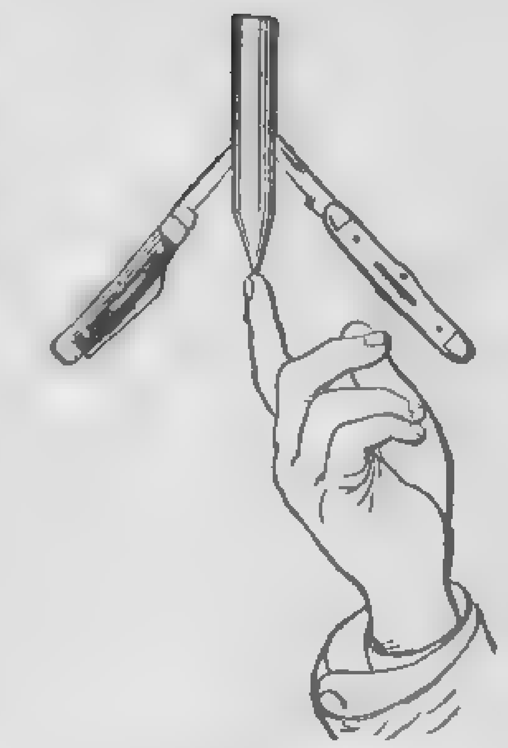


FIG. 72.

7. What is the most stable position of a brick? the least stable position? Why?

8. In what state of equilibrium is a pendulum at rest? Why?

9. Why is a mucilage bottle made low and given a wide base?

FALLING BODIES

90. Galileo's early experiments. Many of the familiar and important experiences of our lives have to do with falling bodies. Yet when we ask ourselves the simplest question which involves quantitative knowledge about gravity, such as, for example, Would a stone and a piece of lead dropped from the same point reach the ground at the same time or at different times? most of us are uncertain as to the answer. In fact, it was the asking and the answering of this very question by Galileo, about 1590, which may be considered as the starting point of modern science.

Ordinary observation teaches that light bodies like feathers fall slowly and that heavy bodies like stones fall rapidly, and up to Galileo's time it was taught in the schools that bodies fall with "velocities proportional to their weights." Not content with book knowledge, however, Galileo experimented with falling bodies himself. In the presence of the professors and students of the University of Pisa he dropped balls of different sizes and materials from the top of the tower of Pisa (Fig. 73), at a height of 180 feet, and found that they fell in almost the same time. He showed that even very light

bodies, such as paper, fall with velocities which approach more and more nearly those of heavy bodies the more compactly they are wadded together. From these experiments he inferred that *all bodies, including the lightest, would fall at the same rate if it were not for the resistance of the air.*

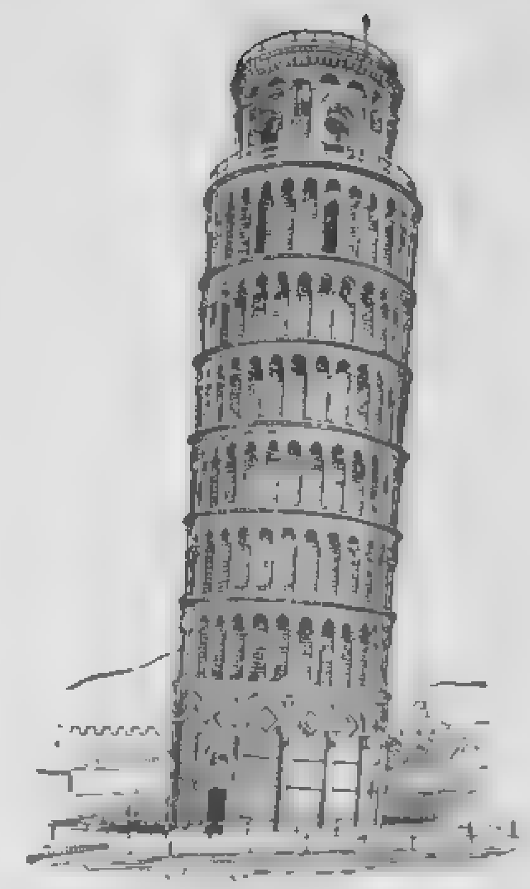


FIG. 73. Leaning tower of Pisa, from which were performed some of Galileo's famous experiments on falling bodies

That the air resistance is, indeed, the chief factor in the slowness of fall of feathers and other light objects can be shown by pumping the air out of a tube containing a feather (or some small pieces of tissue paper) and a coin (Fig. 74). The more complete the exhaustion, the more nearly do the feather and the coin fall side by side when the tube is inverted. The air pump, however, was not invented until sixty years after Galileo's time.

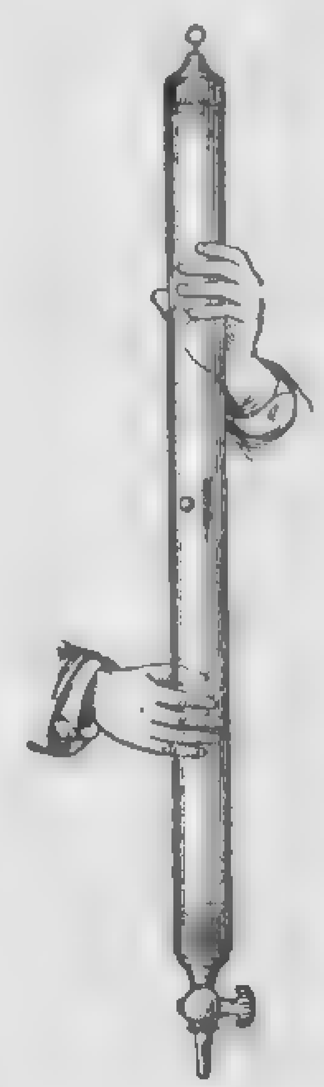


FIG. 74. Feather and coin fall together in a vacuum

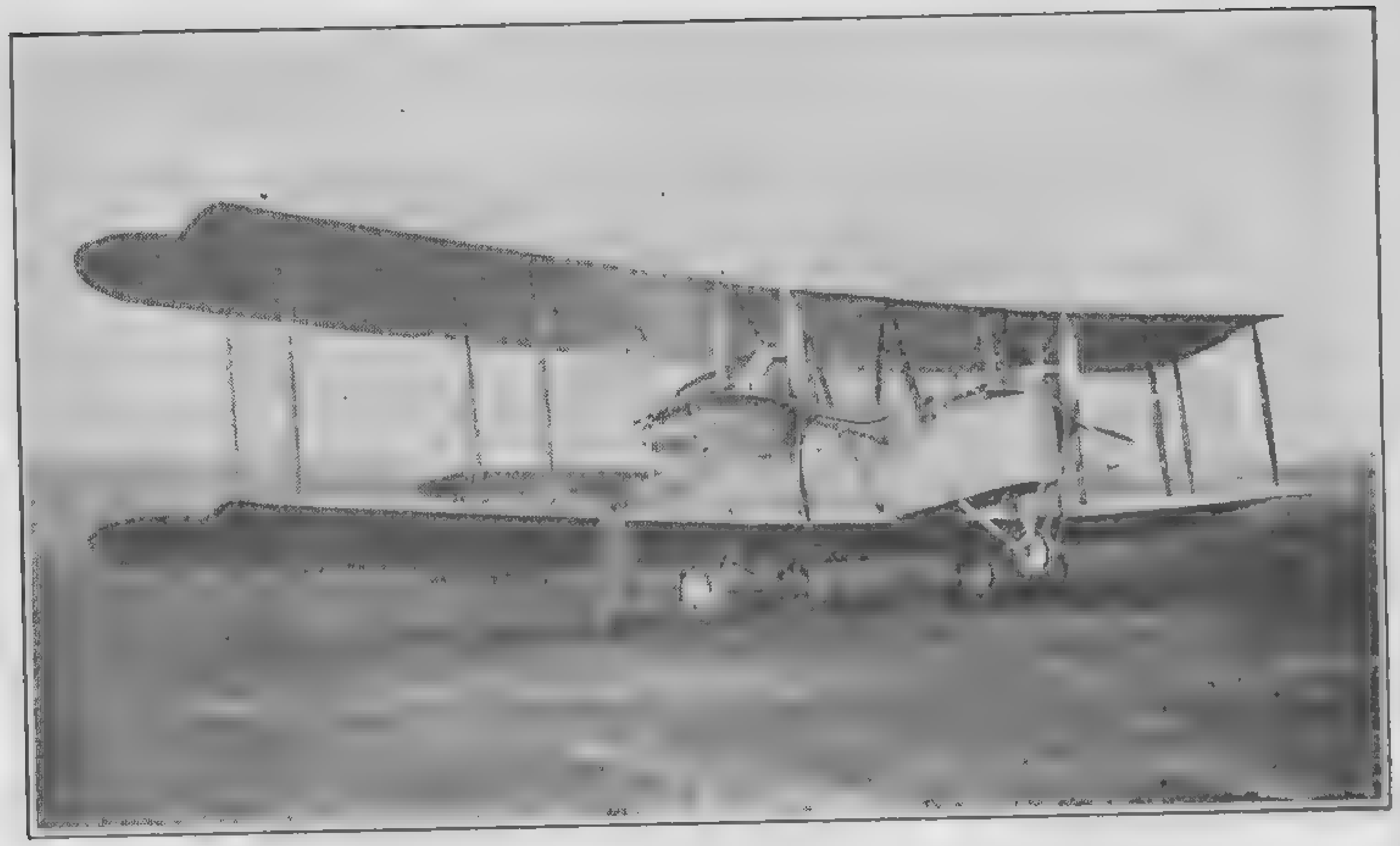
91. Exact proof of Galileo's conclusion. The correctness of Galileo's conclusion can be demonstrated in still another way, one which he himself used.

Let balls of steel and wood (preferably at least an inch in diameter) be started together down the inclined plane of Fig. 75. They will be found to keep together all the way down. (If they roll in a narrow groove, they should have the same diameter; if on a wide track, the size is immaterial.) This experiment differs from that of the freely falling bodies only in that the resistance of the air is here more nearly negligible because of the fact that the balls are moving more slowly.

In order to make them move still more slowly and at the same time to eliminate completely all possible effects due to

GALILEO (1564–1642)

Great Italian physicist, astronomer, and mathematician; "founder of experimental science"; son of an impoverished nobleman of Pisa; studied medicine in early youth, but forsook it for mathematics and science; was professor of mathematics at Pisa and at Padua; discovered the laws of falling bodies and the laws of the pendulum; was the creator of the science of dynamics; constructed the first thermometer; first used the telescope for astronomical observations; discovered Jupiter's satellites and the spots on the sun. Modern physics begins with Galileo



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THE VICKERS-VIMY AIRPLANE

The first nonstop transatlantic airplane flight was made on June 14, 1919, from St. John's, Newfoundland, to Clifden, Ireland, — a distance of 1890 miles. This historic flight, the longest then made, was accomplished in 15 hours 57 minutes, through fog and sleet, at an average speed of 118.5 miles per hour, — a feat that won the $50,000 prize which had been offered for nearly five years by the London *Daily Mail*. The plane was driven by two 360-horse-power Rolls-Royce motors and carried 865 gallons of gasoline. It was piloted by Captain John Alcock and navigated by Lieutenant Arthur W. Brown. This airplane had a wing spread of 67 feet and a length of 42 feet 8 inches

the friction of the plane, Galileo suspended the different balls as the bobs of pendulums of exactly the same length and started them swinging through equal arcs, thus performing the first experiment of § 83. Since now the bobs, as they pass through any given position, are merely moving very slowly down identical inclined planes (Fig. 63), it is clear that this is only a refinement of the last experiment. Galileo thus found, as we did, that the times of fall — that is, the *periods* of the pendulums are exactly the same.

From the preceding experiment we conclude with Galileo and with Newton (who performed it with the utmost care a

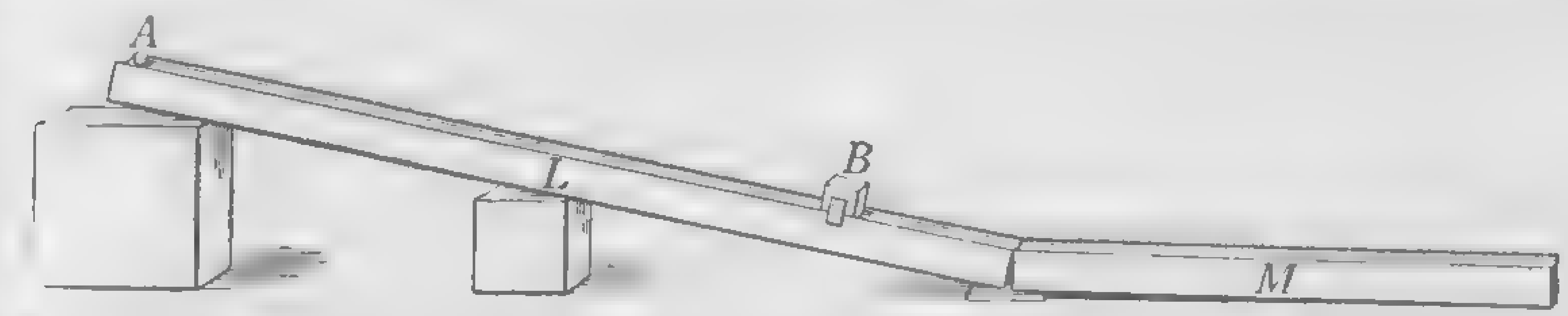


FIG. 75. Spaces traversed and velocities acquired by falling bodies in one, two, three, etc. seconds

hundred years later) that *in a vacuum the velocity acquired per second by a freely falling body is exactly the same for all bodies.*

92. Relation between distance and time of fall. Having discovered that, barring air resistance, all bodies fall in exactly the same way, we shall next try to find what relation exists between distance and time of fall; and since a freely falling body falls so rapidly as to make direct measurements upon it difficult, we shall adopt Galileo's plan of studying the laws of falling bodies through observing the motions of a ball rolling down an inclined plane.

Let a grooved board 17 or 18 ft. long be supported as in Fig. 75, one end being about a foot above the other. Let the side of the board be divided into feet, and let the block B be set just 16 ft. from the starting point of the steel ball A. Let a metronome or a clock beating seconds be started, and let the ball be released at the instant of one click of the metronome. If the ball does not hit the block so that the click produced by the impact of the ball coincides exactly with the fifth click of the metronome, alter the

inclination until this is the case (this adjustment may well be made by the teacher before class). Now start the ball again at any click of the metronome, and note that it crosses the 1-foot mark exactly at the end of the first second, the 4-foot mark at the end of the second second, the 9-foot mark at the end of the third second, and hits B at the 16-foot mark at the end of the fourth second (Fig. 76). This can be tested more accurately by placing B successively at the 9-foot, the 4-foot, and the 1-foot mark and noting that the click produced by the impact coincides exactly with the proper click of the metronome.

We conclude, then, with Galileo, that *the whole distance traversed by a falling body in any number of seconds is equal to*

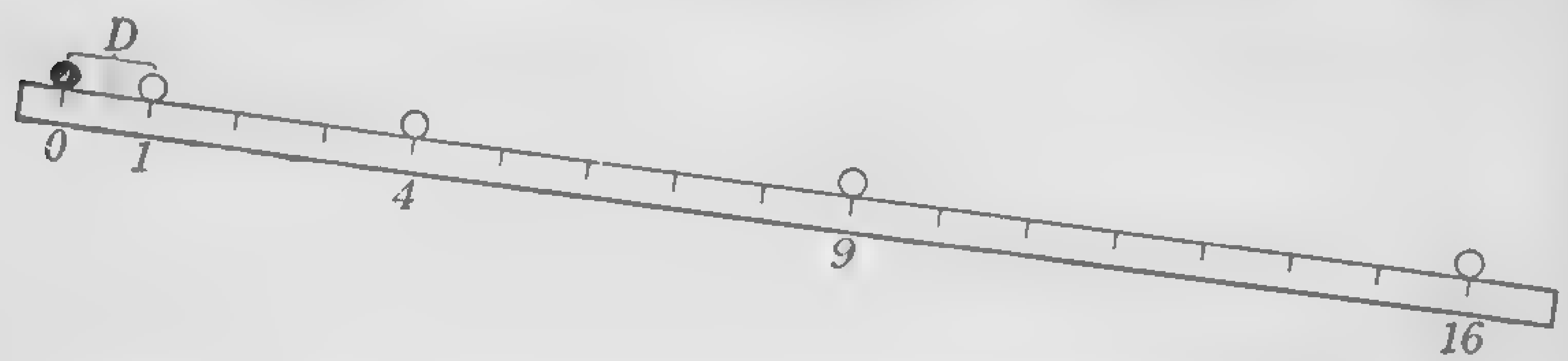


FIG. 76. Total distances traversed during four successive seconds

the distance traversed during the first second times the square of the number of seconds; that is, if D represents the distance traversed during the first second, S the total space, and t the number of seconds, then $S = Dt^2$.

93. Relation between velocity and time of fall. In the last paragraph we investigated the distances traversed in one second, two seconds, three seconds, and so on. Let us now investigate the *velocities* acquired on the same inclined plane in one second, two seconds, three seconds, and so on.

Let a second grooved board M be placed at the bottom of the incline, in the manner shown in Fig. 75. To eliminate friction the board should be given a slight slant, just sufficient to cause the ball to roll along it with uniform velocity. Let the ball be started at a distance D up the incline, D being the distance which in the last experiment it was found to roll during the first second. It will then just reach the bottom of the incline at the instant of the second click. Here it will be freed from the influence of gravity

and will therefore move along the lower board with the velocity which it had at the end of the first second. It will be found that when the block is placed at a distance exactly equal to 2 D from the bottom of the incline, the ball will hit it at the exact instant of the third click of the metronome, that is, exactly 2 sec. after starting; hence the velocity acquired in 1 sec. is 2 D (Fig. 77 (1)). If the ball is started at a distance 4 D up the incline, it will take it 2 sec. to reach the bottom, and it will roll a distance 4 D in the next second; that is, in 2 sec. it acquires a velocity 4 D (Fig. 77 (2)). In 3 sec. it will be found to acquire a velocity 6 D, etc. (Fig. 77 (3)).

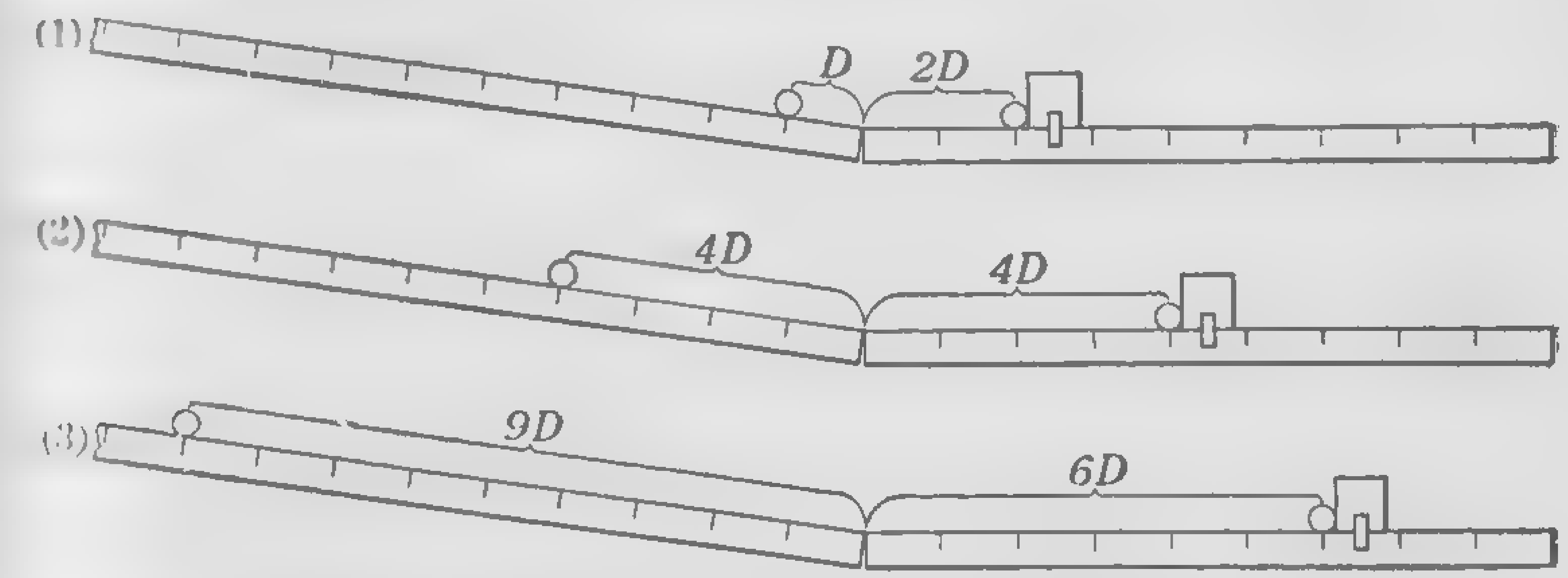


FIG. 77. Velocity at the close of successive seconds

The foregoing experiment shows that the precise meaning of the word "velocity" is *instantaneous rate of motion.* It is numerically equal to the distance through which the body will move per second provided that, at the instant considered, its rate of motion becomes uniform, as was the case in the experiment at the end of the first, second, and third seconds.

The experiment shows, secondly, that the gain in velocity of a falling body each second is the same; thirdly, that the amount of this gain is numerically equal to twice the distance traversed during the first second.

Motion in which velocity is gained or lost at a constant rate (as in the example given above) *is called uniformly accelerated motion.*

In uniformly accelerated motion the gain or loss each second in the velocity is called the acceleration. It is numerically equal to twice the distance traversed during the first second.

94. Formal statement of the laws of falling bodies. Putting together the results of the last two sections, we obtain the following table, in which D represents the distance traversed during the first second in any uniformly accelerated motion.

Number of Seconds (t)	Velocity at the End of Each Second (v)	Gain in Velocity Each Second (a)	Total Distance Traversed (S)
1	$2D$	$2D$	$1D$
2	$4D$	$2D$	$4D$
3	$6D$	$2D$	$9D$
4	$8D$	$2D$	$16D$
...	...	...	...
t	$2tD$	$2D$	t^2D

Since D was shown in § 93 to be equal to half the acceleration a, we have at once, by substituting $\frac{1}{2}a$ for D in the last line of the table,

$$v = at; \tag{1}$$
$$S = \tfrac{1}{2}at^2. \tag{2}$$

These formulas are simply the algebraic statement of the facts brought out by our experiments, but the reasons for these facts may be seen as follows:

Since in uniformly accelerated motion the acceleration a is the velocity in centimeters or feet per second gained each second, it follows at once that when a body starts from rest, the velocity which it has at the end of t seconds is given by $v = at$. This is formula (1).

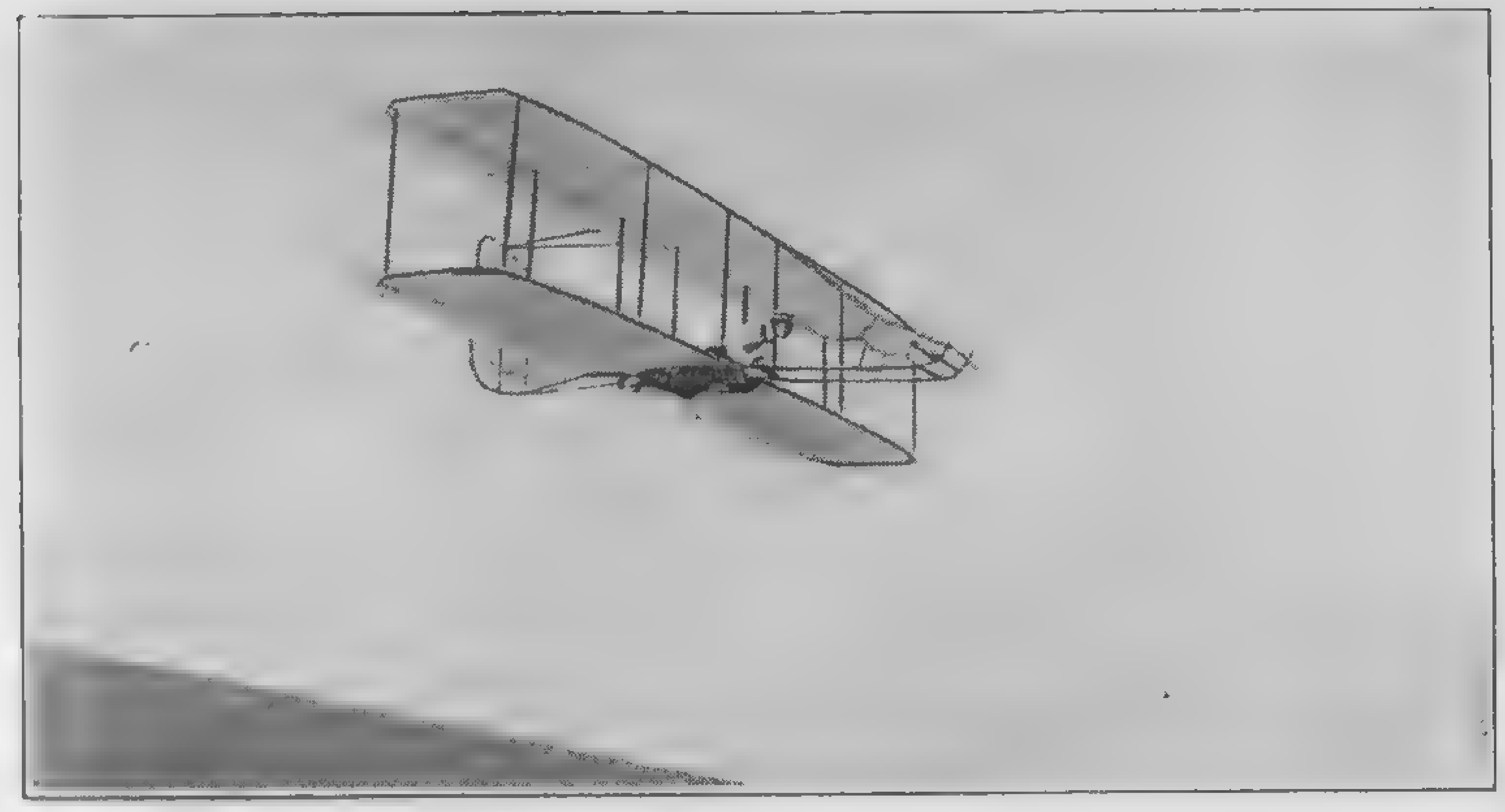
To obtain formula (2) we have only to reflect that distance traversed is always equal to the average velocity multiplied by the time. When the initial velocity is zero, as in this case, and the final velocity is at, average velocity $= (0 + at) \div 2 = \frac{1}{2}at$. Hence

$$S = \tfrac{1}{2}at^2.$$

This is formula (2).

These are the fundamental formulas of uniformly accelerated motion, but it is sometimes convenient to obtain the final velocity v directly from the total distance of fall S, or vice versa. This may be done, of course, by simply substituting in (2) the value of t obtained from (1); namely, v/a. This gives

$$v = \sqrt{2aS}. \tag{3}$$



THE WRIGHT AIRPLANE

The most significant and far-reaching of the advances of the twentieth century, — man's conquest of the air after centuries of failure — was made when the Wright brothers first introduced the principle upon which all successful flight by heavier-than-air machines now depends, namely, control of stability by the warping of wings, or by ailerons (hinged attachments to wings), in connection with the use of a rudder. The upper panel shows one of the original gliders (Wilbur Wright inside) with which the Wrights first mastered the art of gliding (1900–1903) and made more than a thousand gliding flights, some of them 600 feet long, following in this work the principles of gliding flight first demonstrated by Lilienthal and a little later, much more completely, by Chanute of Chicago (1895–1897). The lower panel shows "the first successful power flight in the history of the world" (Orville Wright in the machine, Wilbur running beside it as it rose from the track). Four such flights were made on the morning of December 17, 1903, the longest of which lasted 59 seconds and covered a distance of 852 feet against a 20-mile wind

WILBUR WRIGHT (1867–1912)

ORVILLE WRIGHT (1871–)

The Wright brothers, the men who first solved the age-old problem of mechanical flight, were born in Dayton, Ohio. They received a high-school education, had much mechanical ability, and were flight enthusiasts from early youth, devoting their time almost exclusively to this problem. They were thirty-six and thirty-two years old, respectively, when they made the historic flight at Kitty-hawk, N.C., in 1903. Two years later at Dayton they made the first successful long-distance flight

95. Acceleration of a freely falling body. If in the experiment discussed in § 93 the slope of the plane is made steeper, the results will obviously be precisely the same, except that the acceleration has a larger value. If the board is tilted until it becomes vertical, the body becomes a freely falling body (Fig. 78). In this case the distance traversed the first second is found to be 490 centimeters, or 16.08 feet. Hence the acceleration is 980 cm. per second each second, or 32.16 ft. per second each second. This acceleration of free fall, called the *acceleration of gravity*, is usually denoted by the letter g. For freely falling bodies, then, the three formulas of the preceding paragraph become

$$v = gt, \qquad (4)$$

$$S = \tfrac{1}{2} gt^2, \qquad (5)$$

$$v = \sqrt{2 gS}. \qquad (6)$$

To illustrate the use of these formulas, suppose we wish to know with what velocity a body will hit the earth if it falls from a height of 200 m., or 20,000 cm. From (6) we get

$$v = \sqrt{2 \times 980 \times 20{,}000}$$
$$= 6261 \text{ cm. per second.}$$

The accurate determination of g is never made by direct measurement, for the laws of the pendulum established in § 83 make this instrument by far the most accurate one obtainable for this determination. It is necessary only to measure the length of a long pendulum and the time t between two successive passages of the bob across the mid-point, and then to substitute in

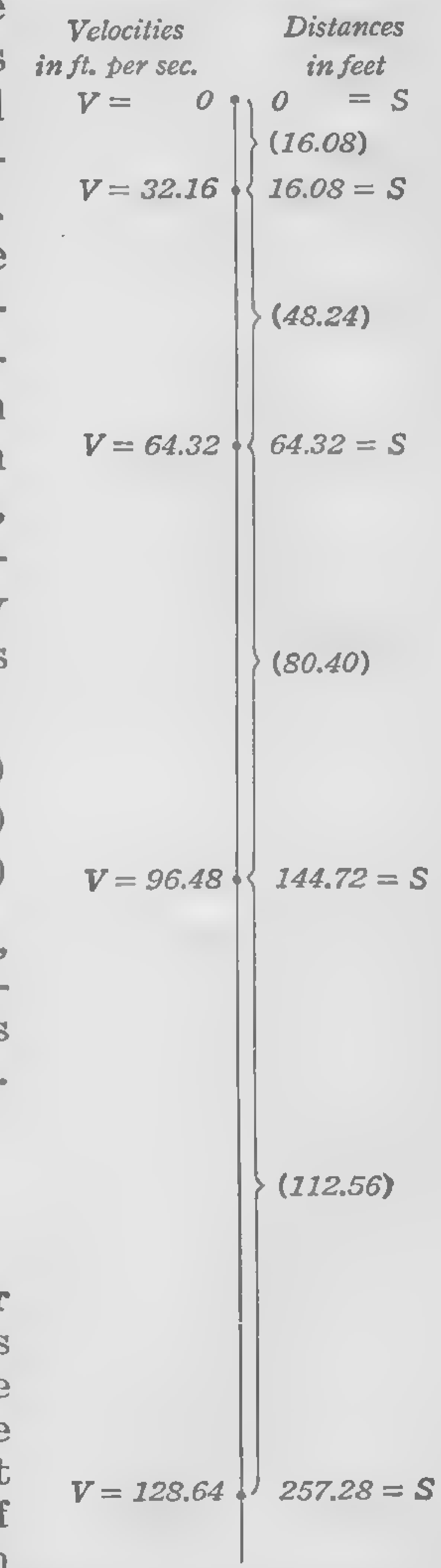


Fig. 78. A freely falling body

the formula $t = \pi \sqrt{l/g}$ in order to obtain g with a high degree of precision. The deduction of this formula is not suitable for an elementary text, but the formula itself may well be used for checking the value of g.

96. Height of ascent. If we wish to find the height S to which a body projected vertically upward will rise, we reflect that the time of ascent must be the initial velocity divided by the upward velocity which the body loses per second, that is, $t = v/g$; and the height reached must be this multiplied by the average velocity $\frac{v+0}{2}$, that is,

$$S = \frac{v^2}{2g}, \text{ or } v = \sqrt{2gS}. \tag{7}$$

Since (7) is the same as (6), we learn that in a vacuum the speed with which a body must be projected upward to rise to a given height is the same as the speed which it acquires in falling from the same height.

97. Path of a projectile. Imagine a projectile to be shot along the line ab (Fig. 79). If it were not for gravity and the resistance

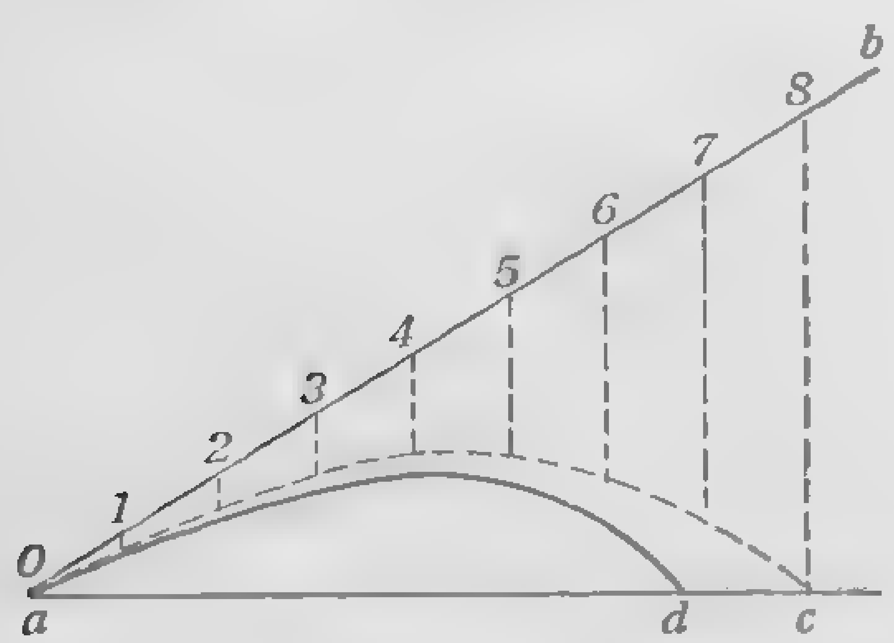


FIG. 79. The path of a projectile

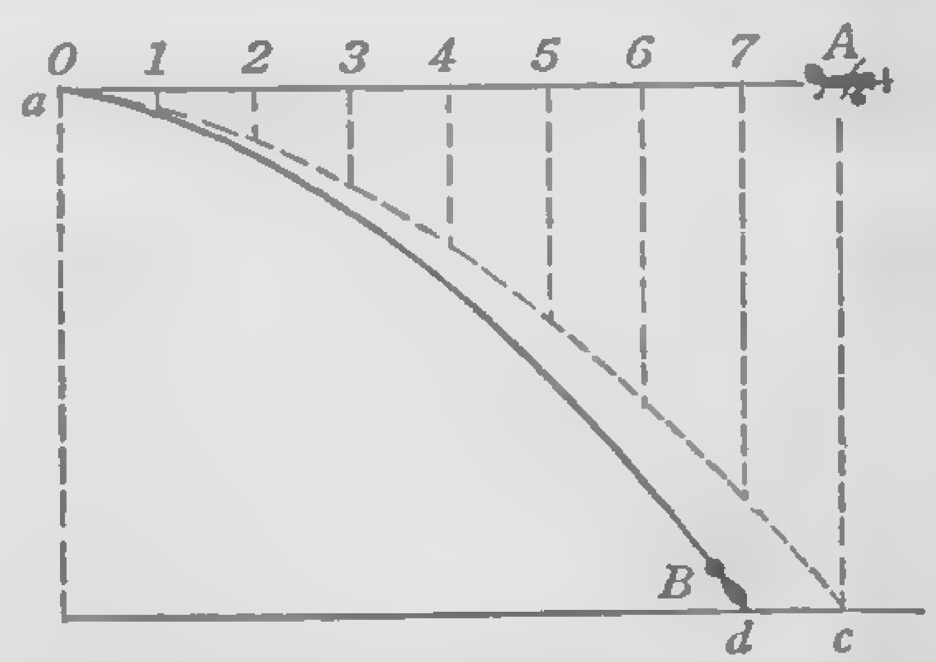


FIG. 80. The bomb B was released at a by the airplane A

of the air, the projectile would travel with uniform velocity along the line ab, arriving at the points 1, 2, 3, etc. at the end of the successive seconds. Because of gravity, however, the projectile would be vertically below these points by the distances 16.08 ft., 64.32 ft., 144.72 ft., etc. Hence it would follow the path indicated by the dotted curve (a parabola). But because of air resistance the height of flight and the range are diminished, and the general shape of the trajectory is similar to the continuous curved line. Fig. 80 represents bomb-dropping by an airplane.

98. The airplane. The simplest way to illustrate the problem of flying is with a boy's kite. Suppose AB (Fig. 81 (1)) is a kite flying in a wind and held by a string; let us suppose also that the kite has no weight, and flies steadily in such a position that its surface makes the angle with the wind denoted by i. Now it is well known that the effect of the wind is twofold. It tends to raise the kite and to drive it back. These effects may be represented by the vertical line marked *lift* and the horizontal line marked *drag*. But since the string prevents the wind from doing what it tends to do, the tension in the string must just balance these two forces *lift* and *drag*. We explain this action by saying that the force in the string must

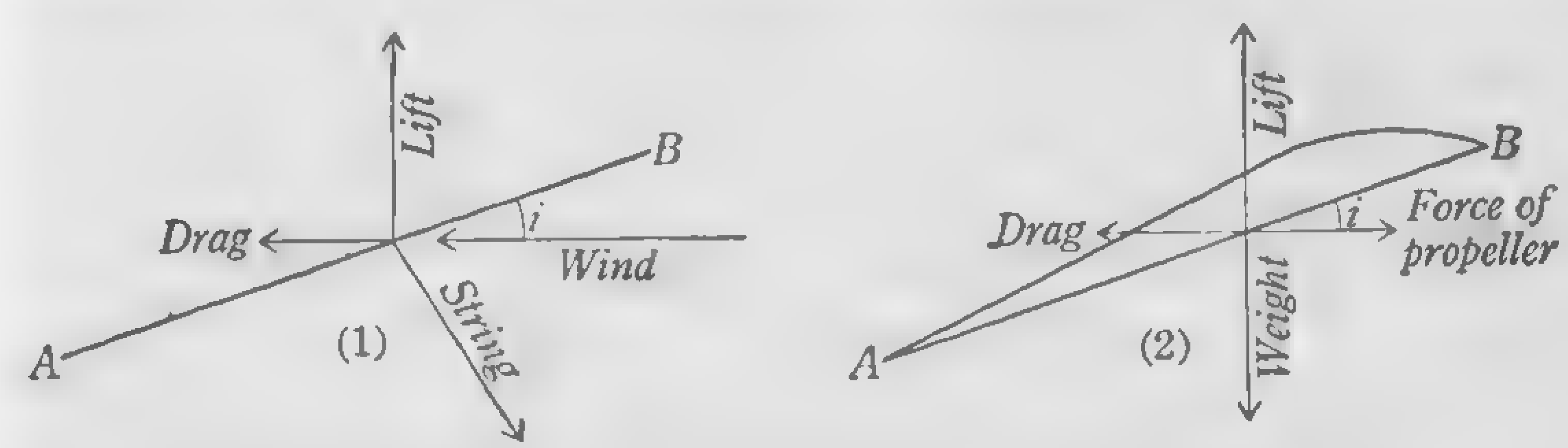


FIG. 81. Forces acting upon a kite and an airplane

be equal to the resultant of *lift* and *drag*, opposite in direction and applied at the same point. This resultant is always nearly perpendicular to AB. The friction of the air on AB is what prevents it from being absolutely perpendicular.

If instead of using one force in a string we use two independent forces, one downward to offset *lift* and the other forward to offset *drag*, we shall obtain the same result. In the airplane (Fig. 81 (2)) this is just what we do. The downward force is the weight of the airplane, which *in the state of steady motion* is just equal and opposite to the lift force, and the forward force is due to the propeller turned by the motor and is equal and opposite to the drag. In brief, *an airplane is supported because the force of the propeller drags it forward and thus causes a relative wind to strike the wing in such a way as to develop a lift force equal to the weight of the plane.*

99. Gliding flight. When the engine stops, the airplane glides to the ground under the action of gravity. Fig. 82 shows the forces acting in such gliding flight in still air when there is no power. The surface is moving downward and forward at some angle i and along the path op. The relative wind po, which in still air is opposite in direction to the path, produces on the wing an effect that may be represented by some *resultant* force oa which, as explained in § 98, is nearly perpendicular to the surface of the plane. If we resolve this force oa into vertical and horizontal components, we get ob and oc; the first, ob, balances the weight, and the second, oc, is the air pressure that now forces the machine forward.

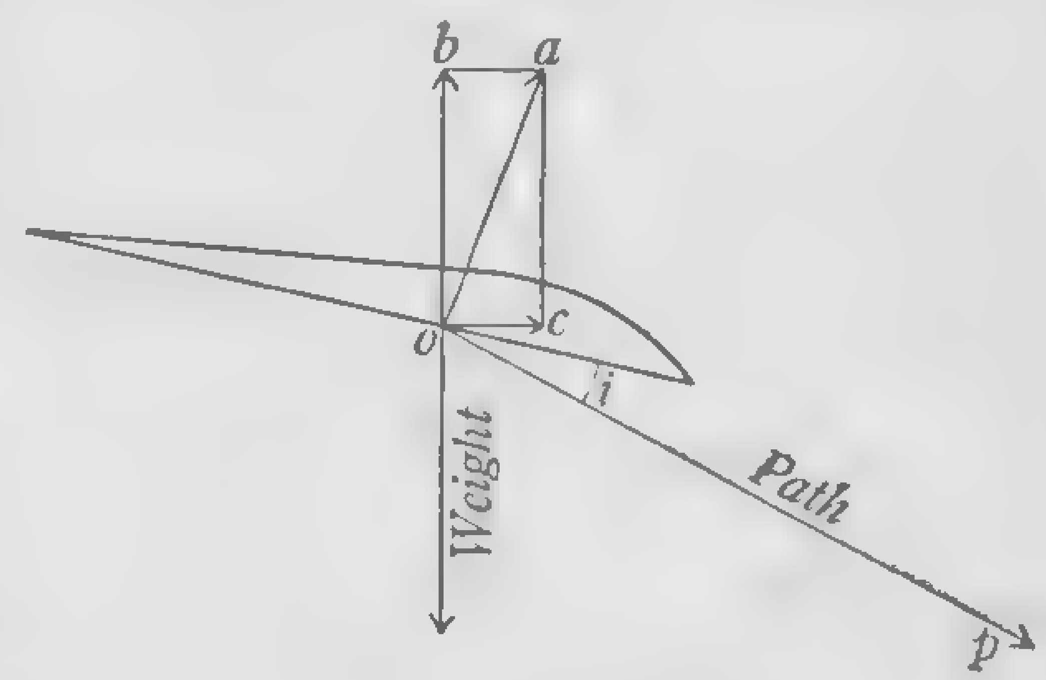


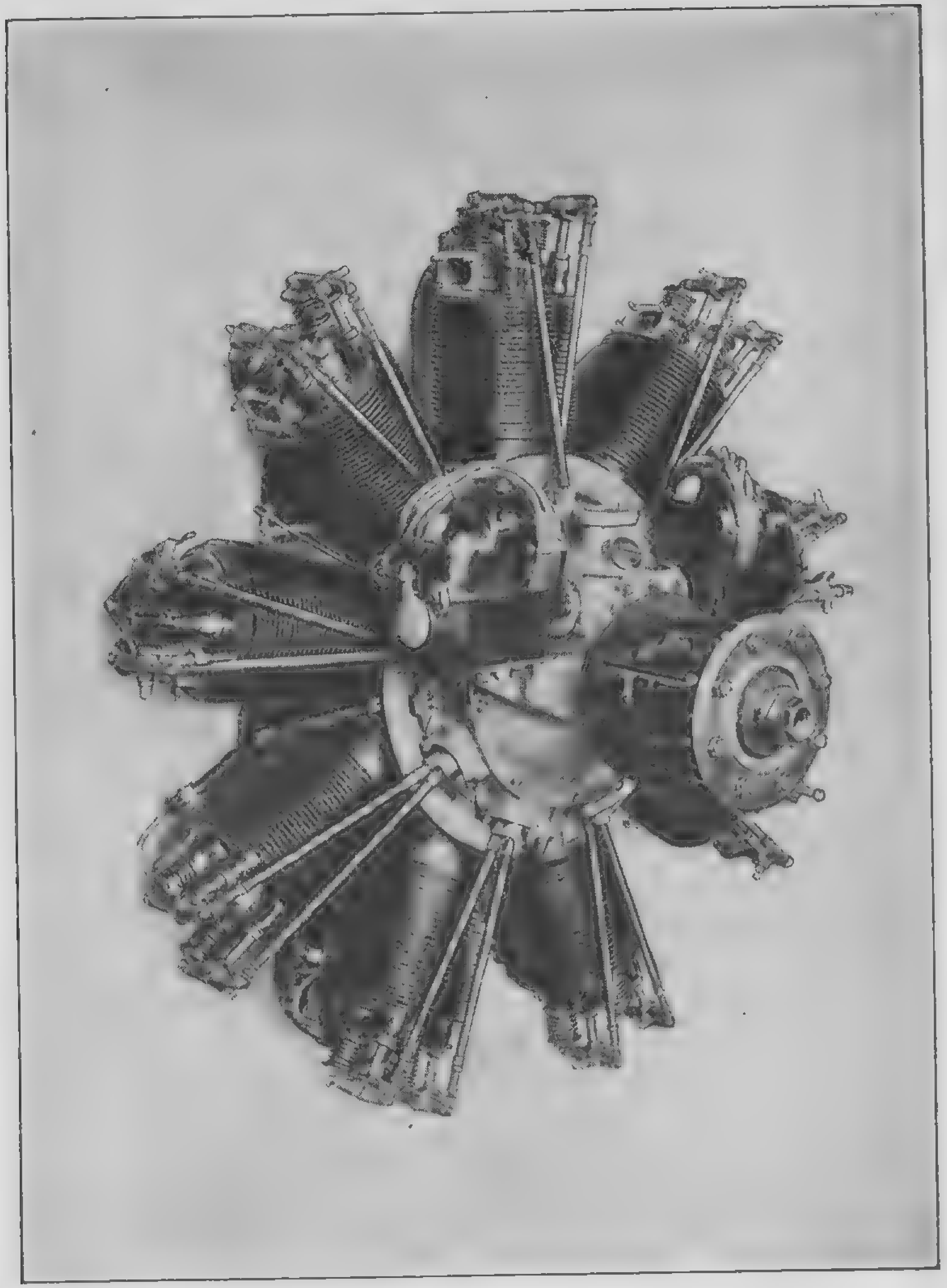
FIG. 82. Gliding flight

100. The principle of the curved ball. There is a further principle involved in flight, which is the same as that underlying the curved ball or Flettner's new *rotor ship*. Let A (Fig. 83 (1)) be a ball that is forced to rotate from right over to left as shown. Let RR (Fig. 83 (2)) be huge cylinders caused to rotate rapidly by machinery while a strong wind is blowing past them. Because of the forward motion of the ball in the one case and the wind on the rotors in the other, the air passes the revolving bodies in the direction shown by the dotted straight arrows. In the lower side of the diagram the air currents which are set up by the drag of the rotating bodies upon the air about them (see dotted circles) obviously oppose the currents indicated by the straight dotted arrows, and thus cause an increase of air pressure on the lower side (see +). On the top side the two sets of currents are in the same direction and cause reduction in air pressure (see −), so that *the spinning bodies are pushed by this difference in pressure in the direction of the vertical arrows and at right angles to the direction of motion of the ball, or the direction of the relative wind.*

While an airplane wing is not a rotating body, the shape which is given it is such that its forward motion tends to cause the air to circulate around it from right over to left and thus to create, just as in Fig. 83, (1) and (2), an excess of atmospheric pressure on the lower side. This may actually be sufficient to keep the plane

WRIGHT-BELLANCA AIRPLANE

New type of commercial plane; designed for safety, high speed, large load, comfort, and economy; capable of 100 M.P.H.; fuel mileage 8 miles per gallon; passengers sit in a comfortable closed cabin. (Courtesy of the Wright Aeronautical Corporation)



WRIGHT WHIRLWIND ENGINE

200-horse-power, 9-cylinder, air-cooled engine; extensively used for commercial purposes: passenger carrying, photography, mapping, cotton-boll-weevil dusting, and forest-fire patrol. The plane shown on the previous page is equipped with this engine. (Courtesy of the Wright Aeronautical Corporation)

flying horizontally even when its lower face is tipped slightly down, as in Fig. 82. Perhaps an even simpler way of explaining this difference in pressure is with the aid of Bernouilli's principle (Fig. 83). On account of the shape of the wing the *air speed* past the wing is higher on the top side than at the bottom; hence the *air pressure* against the wing is less at the top than at the bottom.

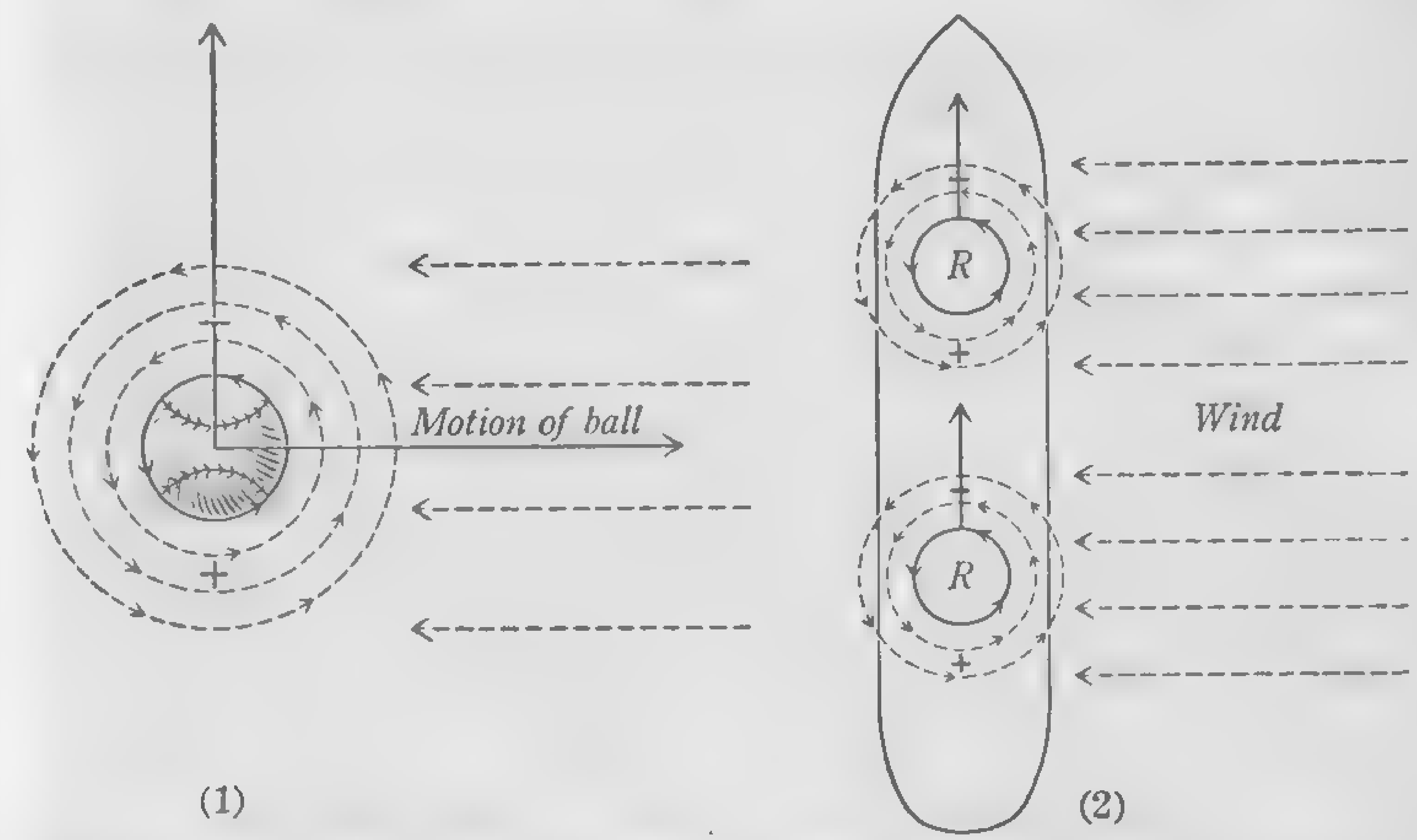


FIG. 83. The curved ball and the rotor ship illustrate Bernouilli's principle, which states that, in general, where the air velocity tangential to a surface is low the air pressure is high, and vice versa

SUMMARY. In a vacuum falling bodies descend at the same rate, irrespective of their mass or size.

The total distance traversed by a falling body in any number of seconds is the distance traversed the first second times the square of the number of seconds, or $S = Dt^2$.

Velocity is the instantaneous rate of motion. It is numerically equal to the distance through which the body will move per second provided that, at the instant considered, its rate of motion becomes uniform. Acceleration is rate of change of velocity.

Uniformly accelerated motion is motion in which velocity is gained or lost at a constant rate. The acceleration is numerically equal to twice the distance traversed during the first second, or $a = 2D$. The velocity gained or lost equals the acceleration times the time, or $v = at$.

If the body starts from rest, its final velocity v and the distance S are related by $v = \sqrt{2aS}$.

For freely falling and freely rising bodies the acceleration is designated by g (= 980 cm. per second each second = 32.16 ft. per second each second).

The total distance traversed always equals AVERAGE VELOCITY times the TIME.

Any projectile falls away from its original path in accordance with the laws of freely falling bodies.

An airplane is supported by the vertical component of the force with which rushing air acts upon its surfaces.

QUESTIONS AND PROBLEMS

1. One boy says a whole brick will fall twice as fast as half a brick because the earth pulls twice as much upon it; a second boy says it will fall half as fast because it is twice as hard to set in motion. What is the truth? Give reasons. Try it.

2. *a.* A boat slid down a shoot-the-chutes, traversing 4 ft. the first second. Without the use of formulas *tell* the answers to the following: (1) How far did the boat slide in 2 sec.? 3 sec.? 4 sec.? 5 sec.? (2) How far did it go during the fifth second? (3) What was the acceleration in ft./sec.^{2} (feet per second each second)? (4) What was the velocity at the close of the fifth second? (5) What was the average velocity during the first five seconds? *b.* Using this average velocity, how far did the boat slide in 5 sec.? Does this answer agree with your answer to the last part of (1)? *c.* Using the velocities at the beginning and at the end of the fifth second, find the average velocity during the fifth second. Knowing this average, state the distance traversed during the fifth second. Does this agree with your answer to (2)?

3. An automobile starting from rest acquired a velocity of 10 mi./hr. (miles per hour) in 5 sec. Assuming the acceleration to be uniform, what was it in mi./hr./sec. (miles per hour per second)? in mi./min./sec.? in ft./min./sec.? in ft./sec./sec.?

4. A ball thrown across the ice started with a velocity of 80 ft./sec. It was retarded by friction at the rate of 2 ft./sec.^{2} For how many seconds did it roll? What was its average velocity during this time? On the basis of average velocity, how far did it go? By the use of $S = \frac{1}{2}at^2$, how far did it go?

5. A skater on reaching a speed of 60 ft./sec. began gliding and came to rest after traversing 600 ft. Find his average velocity during the glide, the time required to traverse the 600 ft., and the acceleration. 3 sec. $S = DT^2$

6. A bullet was fired with a velocity of 2400 ft./sec. from a rifle having a barrel 2 ft. long. Find (1) the average velocity of the bullet while moving the length of the barrel, (2) the time required to move through the barrel, and (3) the acceleration of the bullet while in the barrel. $a = 2$ $V = AT$

7. A boy dropped a stone from a bridge and noticed that it struck the water in just 3 sec. How fast was it going when it struck? What was its average velocity during the 3 sec.? With this average velocity, how far must it have fallen in the 3 sec.? (Take $g = 32$ ft./sec.^{2} and as 9.8 m./sec.^{2} and solve the problem in both English and metric units.) $T = \frac{V}{G}$ $V = GT$

8. (1) How much additional velocity will the pull of the earth impart each second to a freely falling body? What velocity will it take away each second from a freely rising body? (2) A bullet is fired vertically upward with a velocity of 2400 ft./sec. Assuming no air resistance, find (*a*) how long it will take the pull of the earth to bring the bullet to rest, (*b*) the average velocity during the ascent, (*c*) the height to which the bullet rises, using average velocity and time of ascent, and (*d*) the height of ascent, using $S = \frac{1}{2}gt^2$. (Take $g = 32$ ft./sec.^{2})

9. How far will a body fall from rest during the first half second?

10. A baseball was thrown vertically into the air with a velocity of 160 ft./sec. How many seconds did it remain in the air? (Take $g = 32$ ft./sec.^{2}) $T = \frac{V}{g} = \frac{160}{32}$ · 5 sec.

11. A baseball was thrown upward. It remained in the air for 6 sec. With what velocity did it leave the hand? How high did it go? (Take $g = 32$ ft./sec.^{2})

12. With what velocity must a ball be shot upward to rise to the height of the Washington Monument (555 ft.)? How long before it will return? (Take $g = 32$ ft./sec.^{2}) $V = \sqrt{2gs} = \sqrt{2 \times 32}$

13. A ball was batted horizontally with a velocity of 100 ft./sec. from the top of a tower 144 ft. high. Plot its path on the way to the ground, assuming no air resistance.

Newton's Laws of Motion

101. First law: inertia. It is a matter of everyday observation that bodies in a moving train tend to move toward the forward end when the train stops and toward the rear end when the train starts; that is, bodies in motion tend to keep on moving, and bodies at rest to remain at rest.

Again, a block will go farther when driven with a given blow along a surface of glare ice than when knocked along an asphalt pavement. The reason which everyone will assign for this is that there is more friction between the block and the asphalt than between the block and the ice. But when would the body stop if there were no friction at all?

Astronomical observations furnish the most convincing answer to this question, for we cannot detect any retardation at all in the motions of the planets as they swing round the sun through empty space.

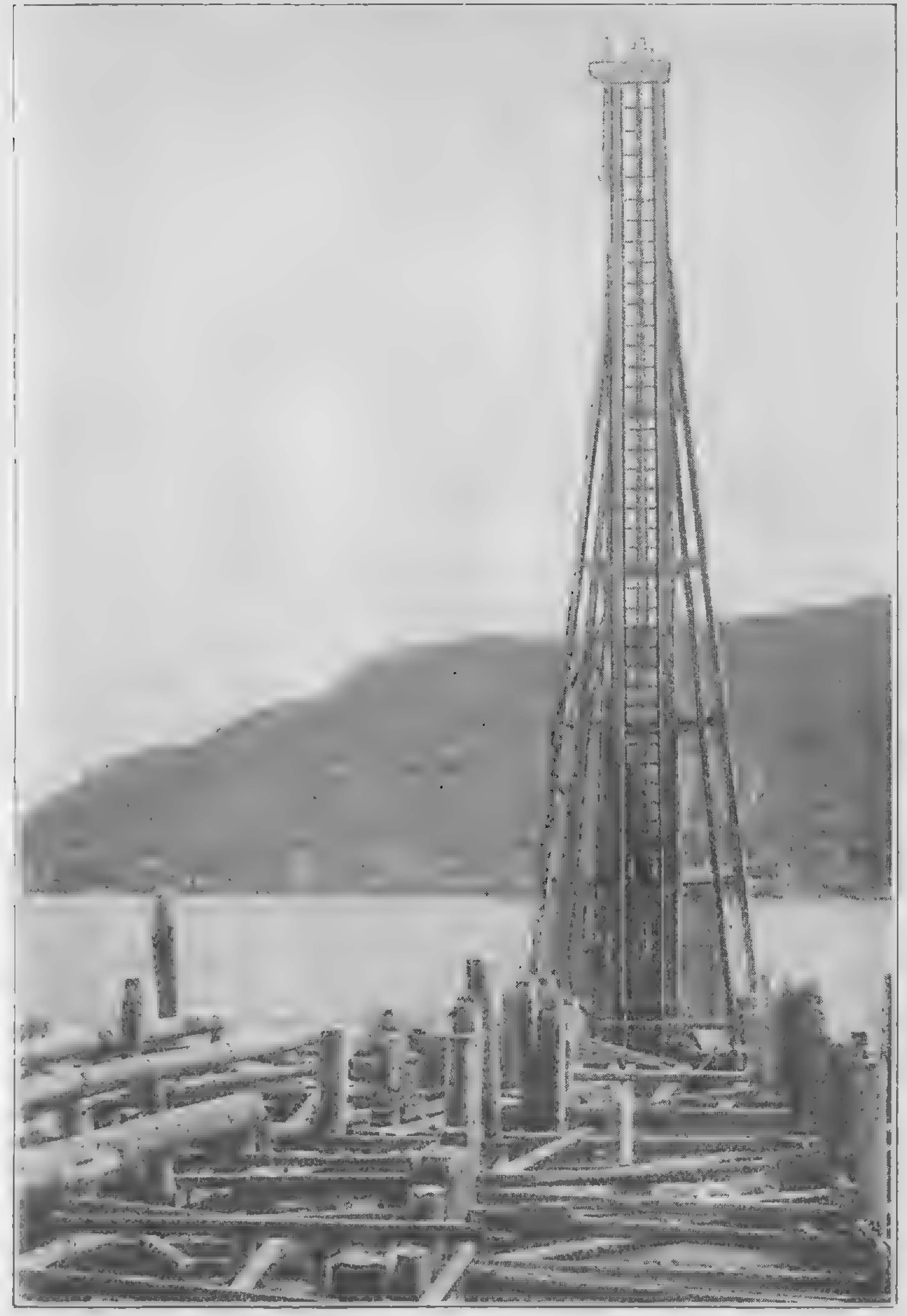
Furthermore, since mud flies off *tangentially* from a rotating automobile wheel, or water from a whirling grindstone, and since, too, we have to lean inward to prevent ourselves from falling outward in going round a curve, it appears that bodies in motion tend to maintain not only the *amount* of their motion but also the *direction* (see gyrocompass opposite page 239).

In view of observations of this sort Sir Isaac Newton in 1686 formulated the following statement and called it the first law of motion:

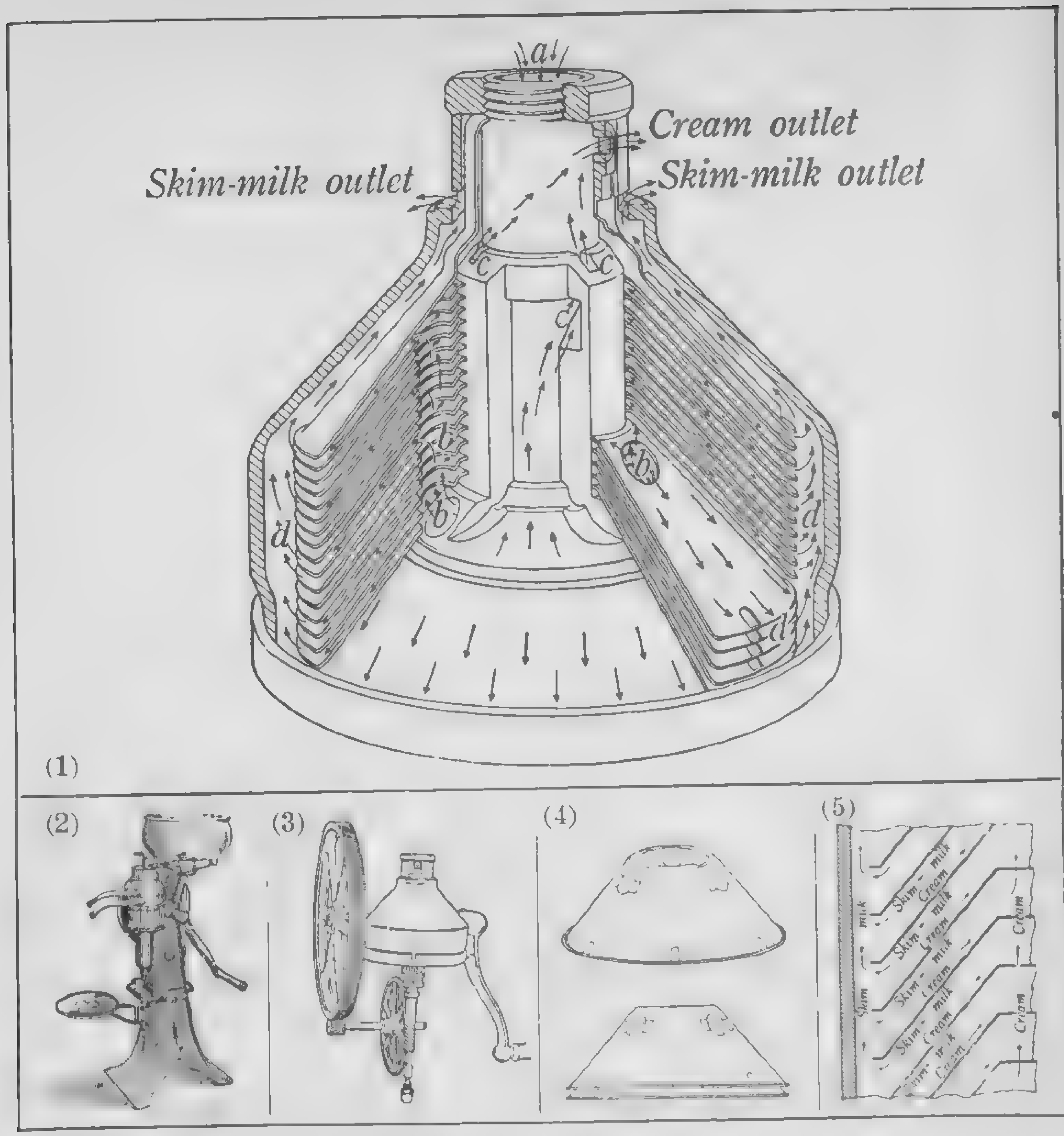
Every body continues in its state of rest or of uniform motion in a straight line unless impelled by external force to change that state.

This property, which all matter possesses, of resisting any attempt to start it if at rest, to stop it if in motion, or in any way to change either the direction or the amount of its motion, is called inertia.

102. Centrifugal and centripetal force. It is inertia alone which prevents the planets from falling into the sun, which



A PILE DRIVER



THE CREAM SEPARATOR

The milk is poured into a central tube (see (1) *a*) at the top of a nest of disks (see (1) and (4)) situated within a steel bowl. The milk passes to the bottom of the central tube, then rises through three series of holes (see (1) *b*, *b*, *b*, etc.) in the nest of disks, and spreads outward into thin sheets between the slightly separated disks. By means of a system of gears (see (3)) the disks and bowl are made to revolve from 6000 to 8000 revolutions per minute. The separation of cream from skim milk is quickly effected in these thin sheets; the heavier skim milk (water, casein, and sugar) is thrown outward by centrifugal force against the *under* surfaces of the bowl disks (see (5)), then passes downward and outward along these under surfaces to the periphery of the bowl (see (1) *d*, *d*, *d*, etc.), and finally rises to the skim-milk outlet. The lighter cream is thereby at the same time displaced inward and upward along the *upper* surfaces of the bowl disks (see (5)), then passes over the inner edges of the disks to slots (see (1) *c*, *c*, *c*, etc.) on the outside of the central tube, finally rising to the cream outlet, which is above the outlet for the skim milk (see (1) and (2))

causes a rotating sling to pull hard on the hand until the stone is released, and which then causes the stone to fly off tangentially. It is inertia which makes rotating liquids move out as far as possible from the axis of rotation (Fig. 84), which sometimes makes flywheels burst, which makes the equatorial diameter of the earth greater than the polar diameter, which makes the heavier milk move out farther than the lighter cream in the dairy separator (see opposite page), etc. *Inertia manifesting itself in this tendency of the parts of rotating systems to get farther from the center of rotation is called centrifugal force.* It is not a true force, but is merely the inertial reaction to the force tending to pull the body toward the center.

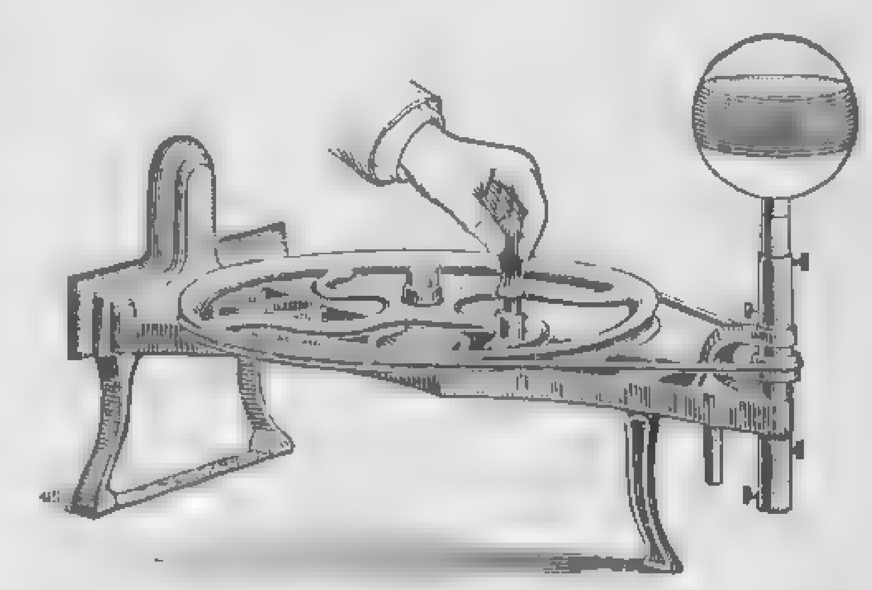


FIG. 84. Illustrating centrifugal force

In *all* rotating systems this tendency of the parts to get farther from the center is counteracted by a force acting toward the center. The gravitational attraction of the sun, for example, is the force which keeps the earth from flying off tangentially into space. *This inward, centrally acting force which comes into play in all rotating systems is called centripetal force.*

103. Momentum. The quantity of motion possessed by a moving body is defined as the product of the mass and the velocity of the body. It is commonly called *momentum.* Thus, a 10-gram bullet moving 50,000 centimeters per second has 500,000 units of momentum; a 1000-kilogram pile-driver moving 1000 centimeters per second has 1,000,000,000 units of momentum; etc. We shall always express momentum in C.G.S. units; that is, as a product of grams by centimeters per second.

104. Second law. Since a 2-gram mass is pulled toward the earth with twice as much force as is a 1-gram mass, and since both, when allowed to fall, acquire the same velocity in a

second, it follows that in this case *the momentums produced in the two bodies by the two forces are exactly proportional to the forces themselves.* In all cases in which forces simply overcome inertias this rule is found to hold. Thus, a 3000-pound pull on an automobile on a level road, where friction may be neglected, imparts in a second just twice as much velocity, and hence twice as much momentum, as a 1500-pound pull does. In view of this relation Newton's second law of motion was stated thus: *Rate of change of momentum is proportional to the force acting, and the change takes place in the direction in which the force acts.*

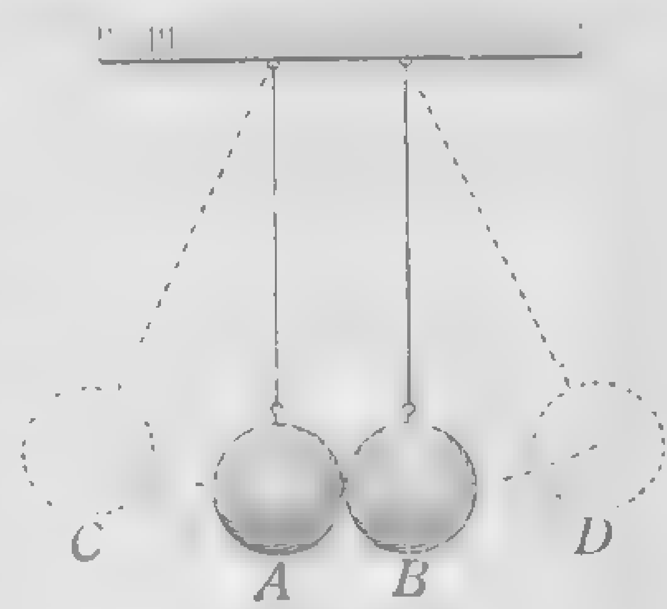


FIG. 85. Illustration of third law

105. The third law. When a man jumps from a boat to the shore, we all know that the boat experiences a backward thrust; when a bullet is shot from a gun, the gun recoils, or "kicks"; when one billiard ball hits another, it loses speed, that is, it is pushed back while the second ball is pushed forward. The following simple experiment will illustrate how effects of this sort may be studied quantitatively:

Let a steel ball *A* (Fig. 85) be allowed to fall from a position *C* against another exactly similar ball *B*. In the impact *A* will lose practically all its velocity, and *B* will move to a position *D*, which is at the same height as *C*. Hence the velocity acquired by *B* is almost exactly equal to that which *A* had before the impact. These velocities would be exactly equal if the balls were perfectly elastic. It is found to be true experimentally that the momentum acquired by *B* plus that retained by *A* is exactly equal to the momentum which *A* had before the impact. The momentum acquired by *B* is therefore exactly equal to that lost by *A*. Since, by the second law, change in momentum is proportional to the force acting, this experiment shows that *A pushed forward on B with precisely the same force with which B pushed back on A.*

Now the essence of Newton's third law is the assertion that in the case of the man jumping from the boat the mass

of the man times his velocity is equal to the mass of the boat times its velocity, and that in the case of the bullet and the gun the mass of the bullet times its velocity is equal to the mass of the gun times its velocity. The truth of this assertion has been established by a great variety of experiments.

Newton stated his third law thus: *To every action there is an equal and opposite reaction.*

Since force is measured by the rate at which momentum changes, this is only another way of saying that *whenever a body acquires momentum some other body acquires an equal and opposite momentum.*

It is not always easy to see at first that setting one body into motion involves imparting an equal and opposite momentum to another body. For example, when a gun is held against the earth and a bullet is shot upward, we are conscious only of the motion of the bullet; the other body in this case is the earth, and its momentum is the same as that of the bullet. On account of the greatness of the earth's mass, however, its velocity is infinitesimal.

106. The dyne. Since the gram of force varies somewhat with locality, it has been found convenient for scientific purposes to take the second law as the basis for the definition of a new unit of force. It is called an absolute, or C.G.S., unit because it is based upon the fundamental units of length, mass, and time, and is therefore independent of gravity. It is named the *dyne* and is defined as *the force which, acting for one second upon any mass, imparts to it one unit of momentum*; or *the force which, acting for one second upon a 1-gram mass, produces a* **change** *in its velocity of 1 centimeter per second.*

107. A gram of force equivalent to 980 dynes. A gram of force was defined as the pull of the earth upon 1 g. of mass. Since this pull is capable of imparting to this mass in 1 sec. a velocity of 980 cm. per second (that is, 980 units of momentum), and since a dyne is the force required to impart in 1 sec. 1 unit of momentum, it is clear that the gram of force is equivalent to 980 dynes of force. The dyne is therefore a very small unit, about equal to the force with which the earth attracts a cubic millimeter of water.

108. Algebraic statement of the second law. If a force F acts for t seconds on a mass of m grams, and in so doing increases its velocity v centimeters per second, then, since the total momentum imparted in a time t is mv, the momentum imparted per second is mv/t; and since force in dynes is equal to momentum imparted per second, we have

$$F = \frac{mv}{t}. \tag{8}$$

But since v/t is the velocity gained per second, it is equal to the acceleration a. Equation (8) may therefore be written

$$F = ma. \tag{9}$$

This is merely stating in the form of an equation that force is measured by rate of change of momentum. Thus, if an engine, after pulling for 30 sec. on a train having a mass of 2,000,000 kg., has given it a velocity of 60 cm. per second, the force of the pull is $2{,}000{,}000{,}000 \times \frac{60}{30} = 4{,}000{,}000{,}000$ dynes. To reduce this force to grams we divide by 980, and to reduce it to kilos we divide, further, by 1000. Hence the pull exerted by the engine on the train $= \frac{4{,}000{,}000{,}000}{980{,}000} = 4081$ kg., or 4.081 metric tons. It will thus be seen that equations (8) and (9) can be used only when the quantities are expressed in absolute units.

Summary. *Newton's three laws of motion.* **First law: Every body continues in its state of rest or of uniform motion in a straight line unless impelled by external force to change that state.**

Second law: Rate of change of momentum is proportional to the force acting, and the change takes place in the direction in which the force acts.

Third law: To every action there is an equal and opposite reaction.

Momentum $= mv =$ mass times velocity.

The absolute C.G.S. unit of force is that force which, acting for one second on a one-gram mass, produces a change in its velocity of one centimeter per second. This unit of force is called the dyne. In C.G.S. units Newton's second law of motion, expressed as a formula, becomes

$$F = \frac{mv}{t} = ma.$$

QUESTIONS AND PROBLEMS*

1. How is inertia manifested when one steps off a moving trolley car while facing toward the rear?

2. Discuss all the manifestations of inertia in connection with the pitching and subsequent batting and catching of a baseball.

3. Explain according to Newton's second law why an engine exerts a greater tractive pull while giving speed to the train than after full speed is attained.

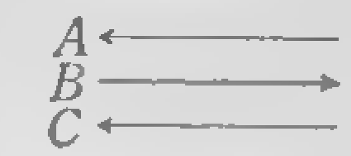


Fig. 86

4. From an analysis of the algebraic statement of Newton's second law explain why in catching a swift baseball your hands are stung less when you let them yield much than when they are held rigidly in place.

5. What principle is applied when one tightens the head of a hammer (1) by bringing the outer end of the handle down quickly on an anvil; (2) by holding the hammer at rest and sharply striking the outer end of the handle endwise with another hammer.

6. If the trains A, B, and C (Fig. 86) are all running 60 mi./hr., what is the velocity of A with reference to B? to C?

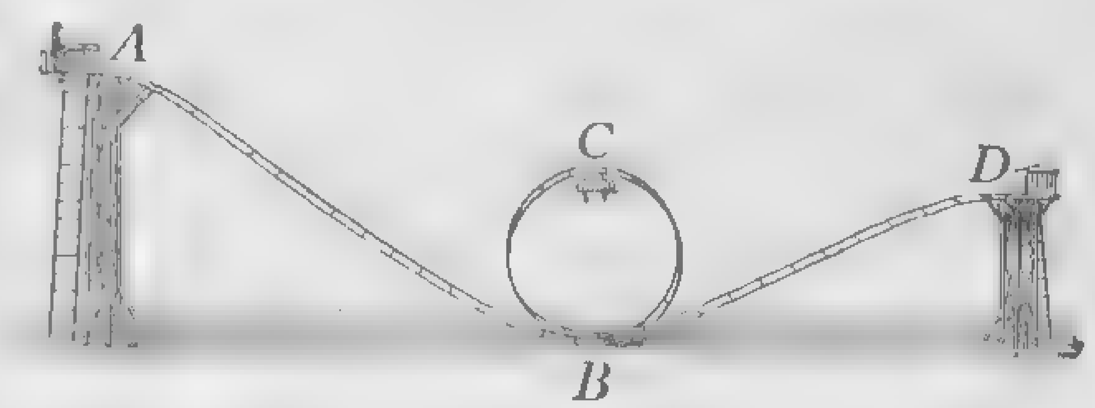


Fig. 87. A very ancient loop-the-loops

7. Why does not the car C of Fig. 87 fall? What carries it from B to D?

8. Why does a flywheel cause machinery to run more steadily? (See opposite page 216.)

9. Balance a calling card on the finger and place a coin upon it. Snap out the card, leaving the coin balanced on the finger. What principle is illustrated?

10. Suspend a weight by a string. Attach a piece of the same string to the bottom of the weight. If the lower string is pulled with a sudden jerk, it breaks; but if the pull is steady, the upper string will break. Explain.

11. State where a body weighs the more: at the poles or at the equator. Give two reasons.

* Supplementary questions and problems for Chapter V are given in the Appendix.

12. Why is a running track banked at the turns?

13. If the earth were to cease rotating on its axis, would bodies on the equator weigh more or less than they do now? Explain.

14. State how the third law is involved in rotary lawn sprinklers.

15. The modern way of drying clothes is to place them in a large cylinder with holes in the sides and then to set the cylinder in rapid rotation. Explain.

16. Explain how reaction pushes the ocean liner and the airplane forward.

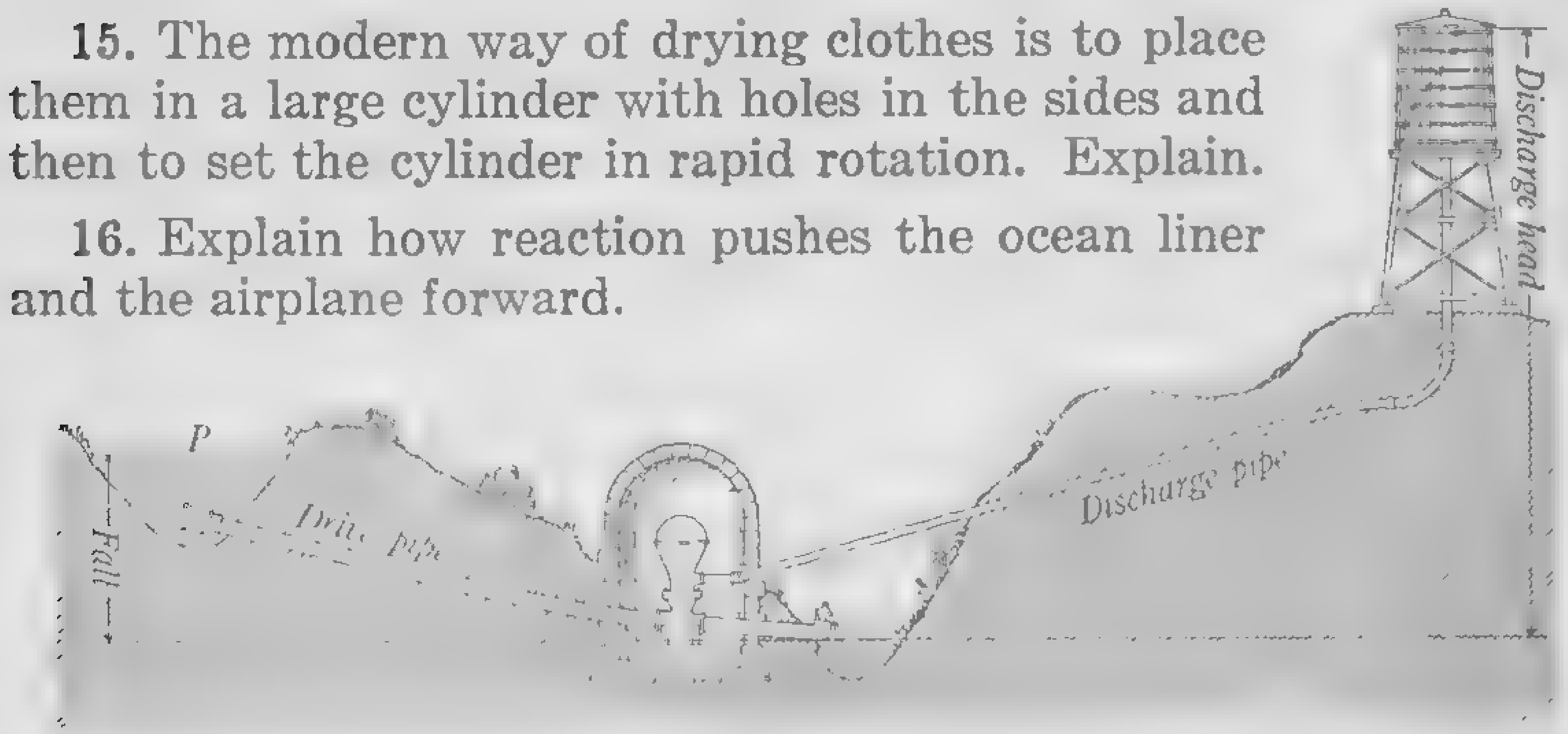


FIG. 88 Hydraulic ram

17. The hydraulic ram (Fig. 88) is a practical illustration of the principle of inertia. With its aid, water from a pond P can be raised into a tank that stands at a higher level than the pond. With the aid of Fig. 89 explain how it works, remembering that the valve V will not close until the stream of water flowing around it acquires sufficient speed.

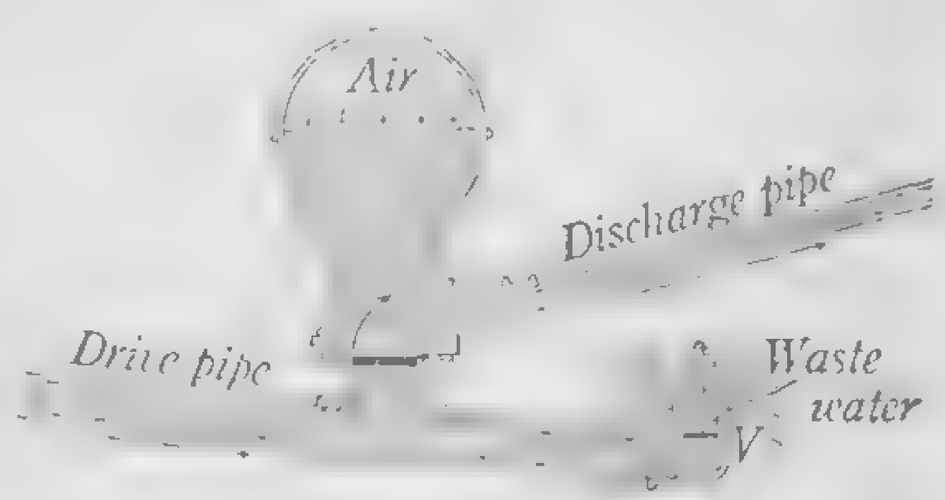


FIG. 89

18. If two men were together in the middle of a perfectly smooth (frictionless) pond of ice, how could they get off? Could one man get off if he were there alone?

19. A rifle weighing 5 lb. discharges a 1-ounce bullet with a velocity of 1000 ft./sec. What will be the velocity of the rifle in the opposite direction? (Solve by Newton's third law.)

20. A pull of a dyne acts for 3 sec. on a mass of 1 g. What velocity does it impart?

21. A force of 1 dyne acts on 1 g. for 1 sec. How far has the gram been moved at the end of the second?

CHAPTER VI

MOLECULAR FORCES*

MOLECULAR FORCES IN SOLIDS; ELASTICITY

109. Tenacities. That the molecules of solids cling together with forces of great magnitude is proved by some of the simplest facts of nature; for solids not only do not expand indefinitely like gases, but to pull their molecules apart often requires enormous forces. Thus, a rod of cast steel 1 centimeter in diameter can be loaded with a weight of 7.8 tons before it will be pulled in two.

The following are the weights in kilograms necessary to break drawn wires of different materials 1 square millimeter in cross section, the so-called relative *tenacities* of the wires.

Lead, 2.6	Platinum, 43	Iron, 77
Silver, 37	Copper, 51	Steel, 91

110. Elasticity. We can obtain additional information about the molecular forces existing in different substances by studying what happens when the weights applied are not large enough to break the wires.

Thus, let a long steel wire (for example, No. 26 piano wire) be suspended from a hook in the ceiling, and let the lower end be wrapped tightly about one end of a meter stick, as in Fig. 90. Let a fulcrum c be placed in a notch in the stick at a distance of about 5 cm. from the point of attachment to the wire, and let the other end of the stick be provided with a knitting needle, one end of which is opposite the vertical mirror scale S. Let enough weights be applied to the pan P to place the wire under slight

* This chapter should be preceded by a laboratory experiment in which Hooke's law is discovered by the pupil for certain kinds of deformation easily measured in the laboratory. See, for example, Experiment 13 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

tension; then let the reading of the pointer p on the scale S be taken. Let three or four kilogram weights be added successively to the pan and let the corresponding positions of the pointer be read. Then let the readings be taken again as the weights are successively removed. In this last operation the pointer will probably be found to come back exactly to its first position.

This characteristic which the steel has shown in this experiment, of returning to its original length when the stretching weights are removed, is an illustration of a property possessed to a greater or less extent by all solid bodies. It is called *elasticity.*

111. Limits of perfect elasticity. If a sufficiently large weight is applied to the end of the wire of Fig. 90, it will be found that the pointer does not return exactly to its original position when the weight is removed. We say, therefore, that steel is *perfectly elastic* only so long as the distorting forces are kept within certain limits, and that as soon as these limits are overstepped it no longer shows perfect elasticity. Different substances differ very greatly in the amount of distortion which they can sustain before they show this failure to return completely to the original shape.

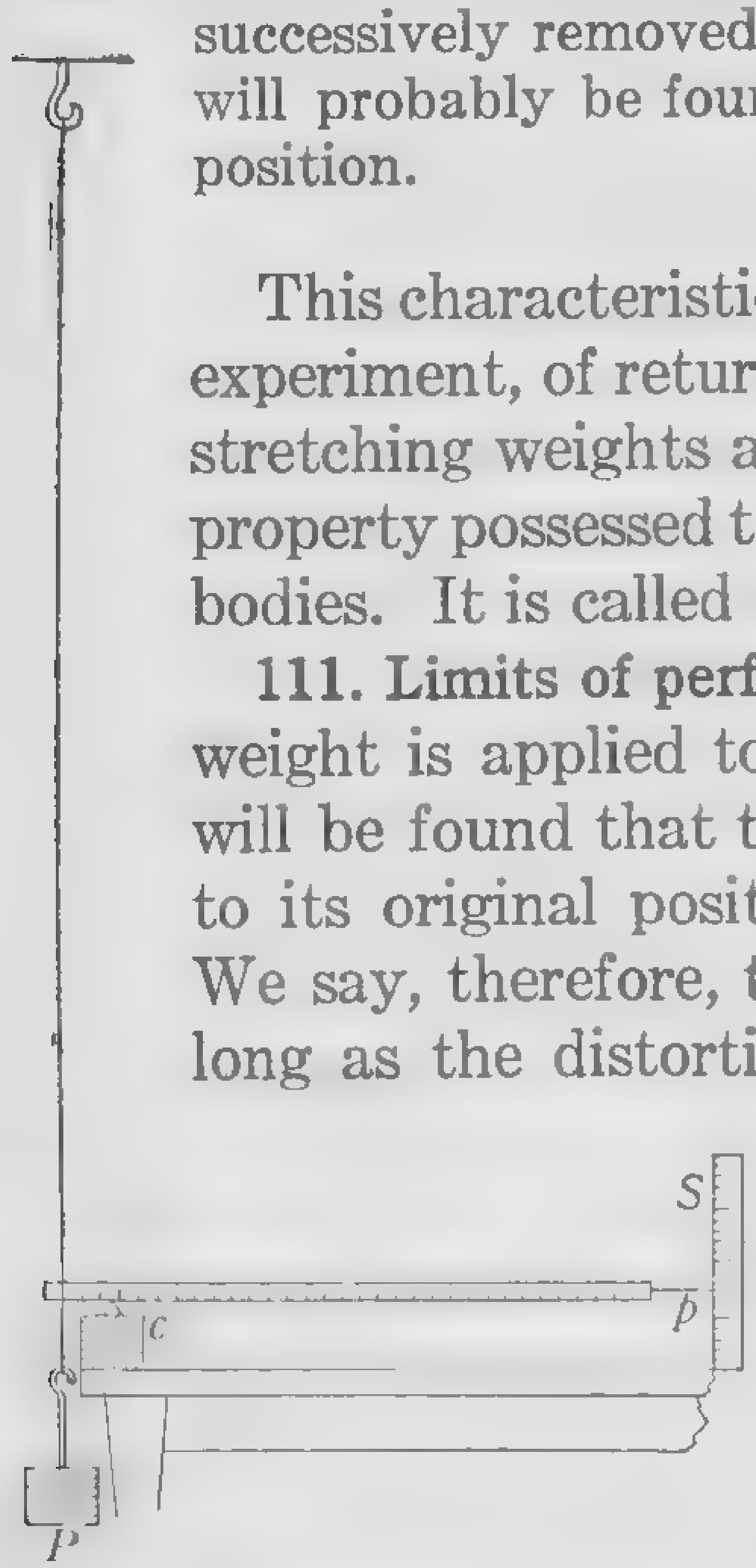


FIG. 90. Elasticity of a steel wire

112. Hooke's law. If we examine the stretches produced by the successive addition of kilogram weights in the experiment of § 110 (Fig. 90), we shall find that these stretches are all equal, at least within the limits of observational error. Very carefully conducted experiments have shown that this law, namely, that the successive application of equal forces produces a succession of equal stretches, holds very exactly for all sorts of elastic displacements so long, and only so long, as the limits of perfect elasticity are not overstepped. This

law is known as Hooke's law, after the Englishman Robert Hooke (1635–1703). Another way of stating this law is the following: *Within the limits of perfect elasticity, elastic deformations of any sort, whether they are twists or bends or stretches, are directly proportional to the forces producing them.* The common spring balance (Fig. 55) is an application of Hooke's law.

113. Cohesion and adhesion. The preceding experiments have brought out the fact that, in the solid condition at least, molecules of the same kind exert attractive forces upon one another. That molecules of unlike substances also exert mutually attractive forces is equally true, as is proved by the fact that glue sticks to wood with tremendous tenacity, mortar to bricks, nickel plating to iron, etc.

The forces which bind *like* kinds of molecules together are commonly called *cohesive forces*; those which bind together molecules of *unlike* kind are called *adhesive forces.* Thus, we say that mucilage sticks to wood because of *adhesion,* and wood itself holds together because of *cohesion.* Again, adhesion holds the chalk to the blackboard; cohesion holds together the particles of the crayon.

SUMMARY. ***Hooke's law.*** **Within the limits of perfect elasticity deformations are directly proportional to the forces producing them.**

Cohesion is the term used to designate the mutual forces of attraction between like molecules.

Adhesion is the term used to designate the mutual forces of attraction between unlike molecules.

QUESTIONS AND PROBLEMS

1. If a given weight is required to break a given wire, how much force is required to break two such wires hanging side by side? to break one wire of twice the diameter?

2. Why are springs made of steel rather than of copper?

3. If the position of the pointer on a spring balance is marked when no load is on the spring, and again when the spring is stretched with a load of 10 g., and if the space between the two marks is then divided into ten equal parts, will each of these parts represent a gram? Why?

4. A broken piece of wrought iron or steel may be welded by heating the broken ends white hot and pounding them together. Gold foil is welded cold in the process of filling a tooth. Explain welding.

5. A piece of broken wood may be mended with glue. What does the glue do?

Molecular Forces in Liquids; Capillary Phenomena

114. Proof of the existence of molecular forces in liquids. The facility with which liquids change their shape might lead us to suspect that the molecules of such substances exert almost no force upon one another, but a simple experiment will show that this is far from true.

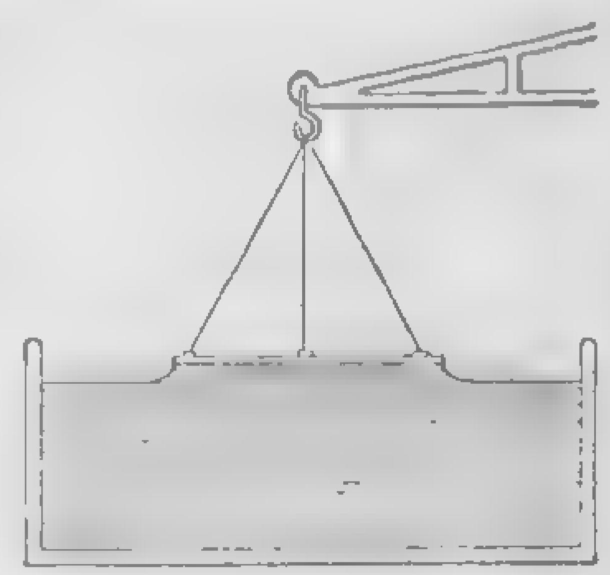


Fig. 91. Illustrating cohesion of water

By means of sealing wax and string let a glass plate be suspended horizontally from one arm of a balance, as in Fig. 91. After equilibrium is obtained let a surface of water be placed just beneath the plate and the beam be pushed down until contact is made. It will be found necessary to add a considerable weight to the opposite pan to pull the plate away from the water. Since a layer of water will be found to cling to the glass, it is evident that the added force applied to the pan has been expended in pulling water molecules away from water molecules, not in pulling glass away from water. Similar experiments may be performed with all liquids. In the case of mercury the glass will not be found to be wet, showing that the cohesion of mercury is greater than the adhesion of glass and mercury.

115. Shape assumed by a free liquid. Since, then, every molecule of a liquid is pulling on every other molecule, any body of liquid which is free to take its natural shape, that is, which is acted on only by its own cohesive forces, must draw itself together until it has the smallest possible surface compatible with its volume; for since every molecule in the surface is drawn toward the interior by the attraction of the

molecules within, it is clear that molecules must continually move toward the center of the mass until the whole has reached the most compact form possible. Now the geometrical figure which has the smallest area for a given volume is a sphere. We conclude, therefore, that if we could relieve a body of liquid from the action of gravity and other outside forces, it would at once take the form of a perfect sphere. This conclusion may be easily verified by the following experiment:

Let alcohol be poured upon the top of water in a wide *flat-sided* bottle. Then with a pipette insert a large globule of oil at the bottom of the layer of alcohol. The oil will be seen to float as a perfect sphere within the body of the liquid (Fig. 92).

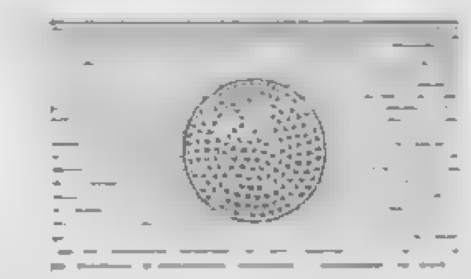


Fig. 92. A spherical globule of oil, freed from action of gravity

Liquids are not commonly observed to take the spherical form because ordinarily the force of gravity is so large as to be more influential in determining their shape than are the cohesive forces. As verification of this statement we have only to observe that as a body of liquid becomes smaller and smaller — that is, as the gravitational forces upon it become less and less — it does indeed tend more and more to take the spherical form. Thus, very small globules of mercury on a table will be found to be almost perfect spheres, and small raindrops or minute *floating* particles of all liquids are very nearly spherical.

116. Contractility of liquid films; surface tension. The tendency of liquids to assume the smallest possible surface furnishes a simple explanation of the contractility of liquid films.

Let a soap bubble 2 or 3 in. in diameter be blown on the bowl of a pipe and then allowed to stand. It will at once begin to shrink in size, and in a few minutes will disappear within the bowl of the pipe. The liquid of the bubble is simply obeying the tendency to reduce its surface to a minimum, a tendency arising entirely from the mutual attractions which its molecules exert upon one another. A candle flame held opposite the opening in the stem of

the pipe will be deflected by the current of air which the contracting bubble is forcing out through the stem.

Again, let a loop of fine thread be tied to a wire ring, as in Fig. 93. Let the ring be dipped into a soap solution so as to form a film across it, and then let a hot wire be thrust through the film

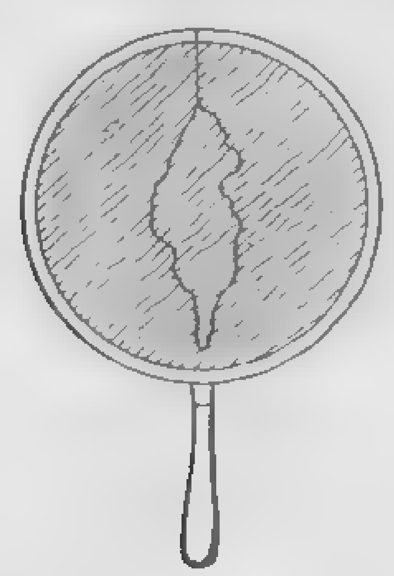


FIG. 93

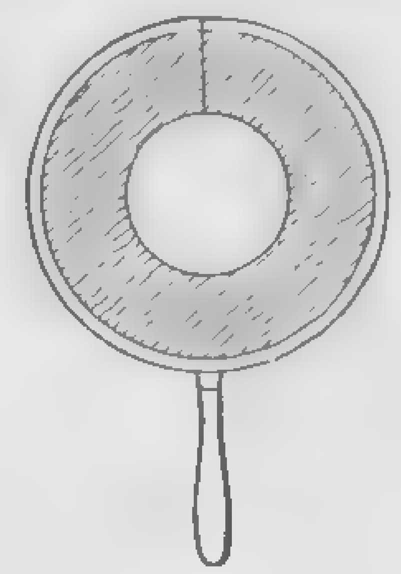


FIG. 94

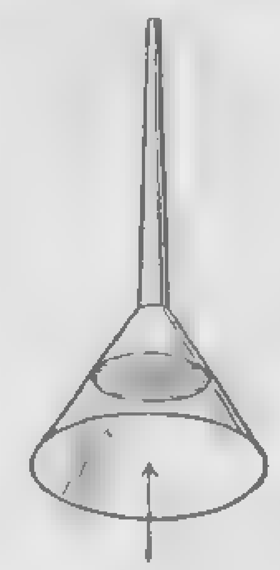


FIG. 95

Illustrating the contractility of soap films

inside the loop. The tendency of the film outside the loop to contract will instantly snap out the thread into a perfect circle (Fig. 94). The reason that the thread takes the circular form is that, since the film outside the loop is striving to assume the

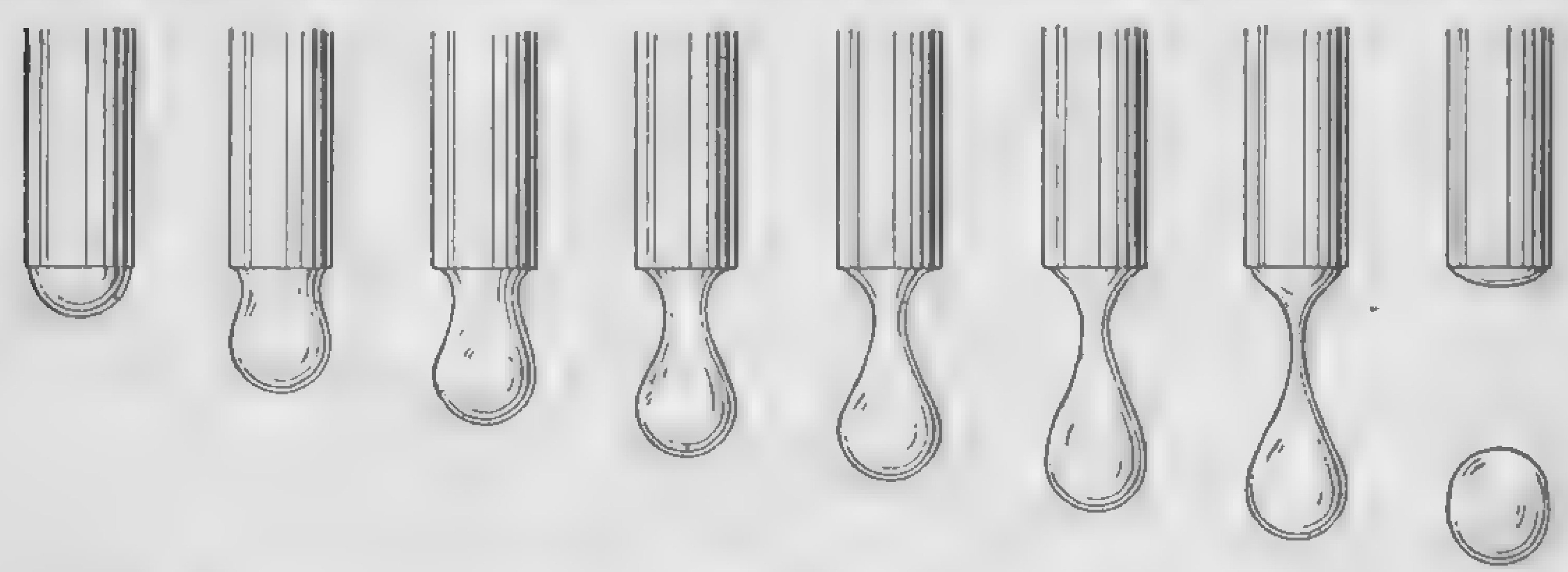


FIG. 96. Some of the stages through which a slowly forming drop passes

smallest possible surface, the area inside the loop must of course become as large as possible. The circle is the figure which has the largest possible area for a given perimeter.

Let a soap film be formed across the mouth of a clean 2-inch funnel, as in Fig. 95. The tendency of the film to contract will be sufficient to lift its weight against the force of gravity.

The tendency of a liquid to reduce its exposed surface to a minimum, that is, *the tendency of any liquid surface to act like*

a stretched elastic membrane, is called *surface tension*. The elastic nature of a film is illustrated in Fig. 96, which is from a motion-picture record of some of the stages through which a slowly forming drop passes. The external layers of molecules act like an elastic bag to hold the rest of the liquid within.

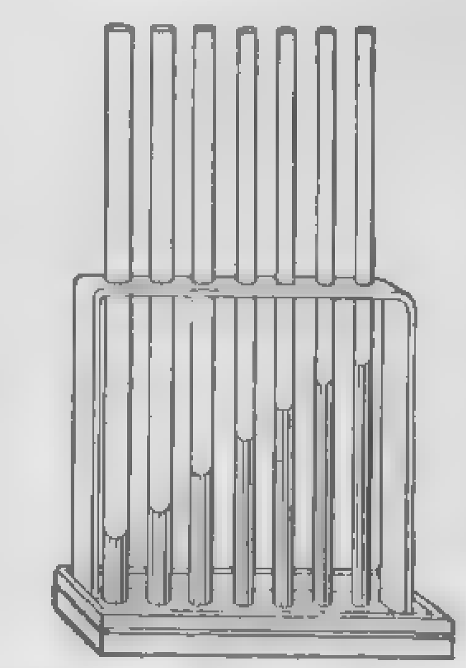


FIG. 97. Rise of liquids in capillary tubes

117. Ascension and depression of liquids in capillary tubes. It was shown in Chapter II that in general a liquid stands at the same level in any number of communicating vessels. The following experiments will show that this rule ceases to hold in the case of tubes of small diameter.

Let a series of capillary tubes of diameter varying from 2 mm. to 1 mm. be arranged as in Fig. 97.

When water or ink is poured into the vessel it will be found to rise higher in the tubes than in the vessel, and it will be seen that the smaller the tube, the greater the height to which the liquid rises. If the water is replaced by mercury, however, the effects will be found to be just inverted. The mercury is depressed in all the tubes, the depression being greater in proportion as the tube is smaller (Fig. 98 (1)). This depression is most easily observed with a U-tube like that shown in Fig. 98 (2).

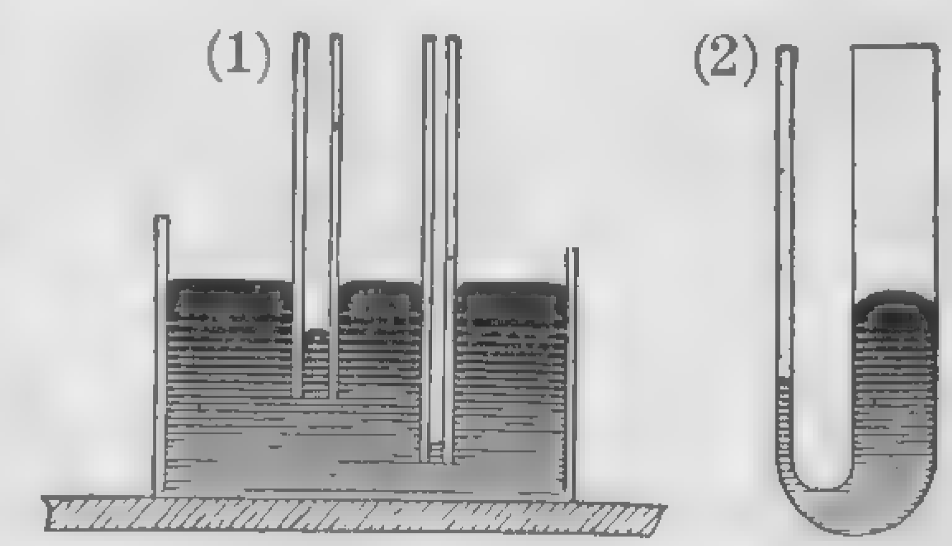


FIG. 98. Depression of mercury in capillary tubes

Experiments have established the following laws:

1. *Liquids rise in capillary tubes when they are capable of wetting them, but are depressed in tubes which they do not wet.*

2. *The elevation in the one case and the depression in the other are inversely proportional to the diameters of the tubes.*

It will be noticed, too, that when a liquid rises, its surface within the tube is concave upward; when it is depressed, its surface is convex upward.

118. Cause of curvature of a liquid surface in a capillary tube. All the effects presented in the last paragraph can be explained by a consideration of cohesive and adhesive forces. However, throughout the explanation we must keep in mind two familiar facts: first, that *the surface of a body of water at rest (for example a pond) is at right angles to the resultant force (that is, gravity) which acts upon it*; secondly, that *the force of gravity acting on a minute amount of liquid is negligible in comparison with the cohesive forces acting within the liquid* (see § 115).

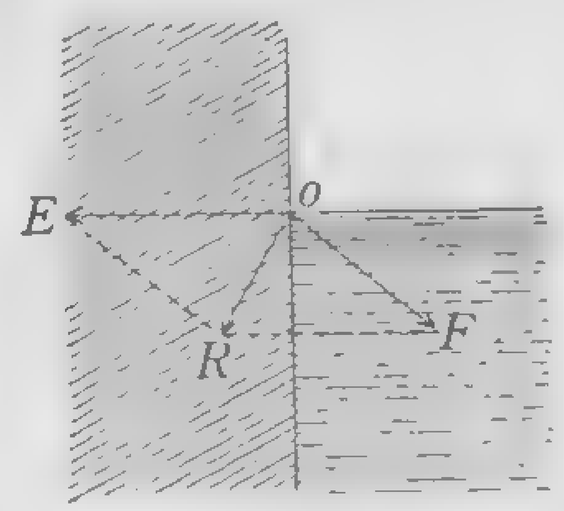


FIG. 99

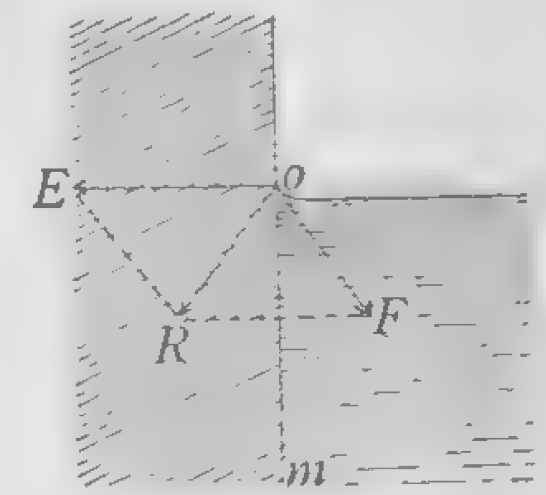


FIG. 100

Condition for elevation of a liquid near a wall

Consider, then, a very small body of liquid close to the point o (Fig. 99), where water is in contact with the glass wall of the tube. Let the quantity of liquid considered be so minute that the force of gravity acting upon it may be disregarded. The force of *adhesion* of the wall will pull the liquid particles at o in the direction oE. The force of *cohesion* of the liquid will pull these same particles in the direction oF. The resultant of these two pulls on the liquid at o will then be represented by oR (Fig. 99) in accordance with the parallelogram law of Chapter V. If, then, the resultant oR of the adhesive force oE and the cohesive force oF lies to the left of the vertical om (Fig. 100), since the surface of a liquid always assumes a position at right angles to the resultant force, the liquid must rise up against the wall as water does against glass (Fig. 100).

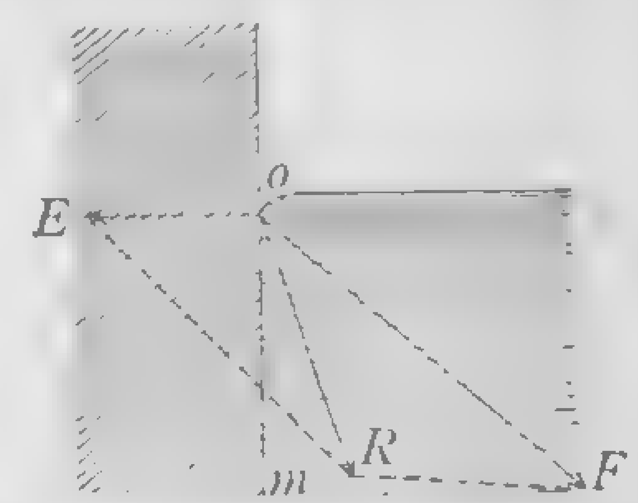
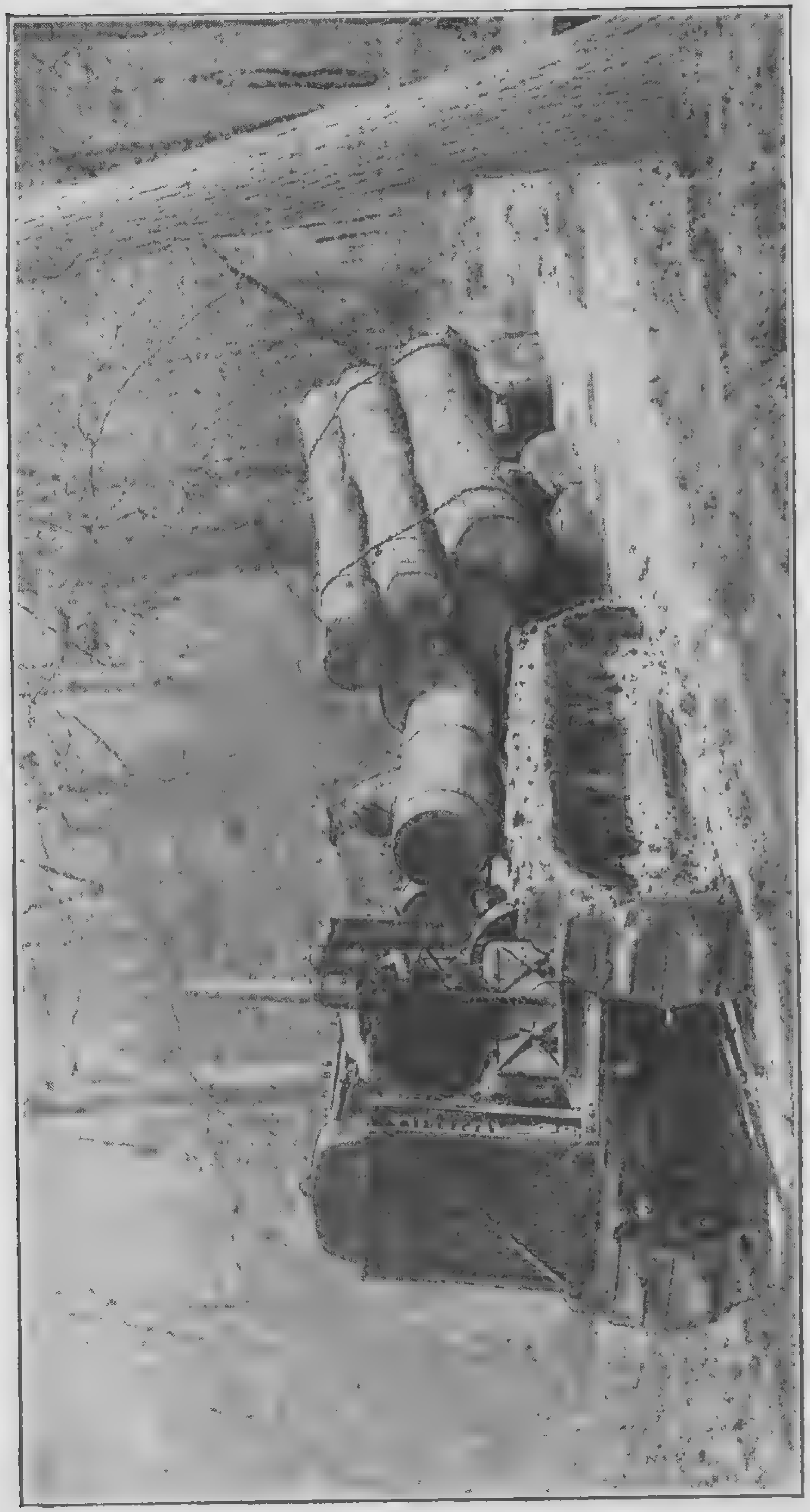


FIG. 101. Condition for the depression of a liquid near a wall

If the cohesive force oF (Fig. 101) is strong in comparison with the adhesive force oE, the resultant oR will fall to the

A SMALL FARM TRACTOR

Farm tractors are used extensively in dry farming, which consists in specially preparing the soil for reception of water and for its retention through the lessening of its rapidity of evaporation. Breaking a hard, compact surface into coarser particles diminishes the amount of moisture that rises by capillary action to the surface to evaporate. (Courtesy of Ford Motor Company)



A CATERPILLAR TRACTOR

The caterpillar tractor is in reality a land locomotive that continuously lays the track upon which it runs. It is possessed of enormous tractive power and does not slip on ice or snow. This form of tractor is being increasingly used in logging not only because of its great power but also because it prevents excessive destruction of the forests and the soil, with the consequent loss of the water which would otherwise be held by the many capillary activities of soil and vegetation

right of the vertical, in which case the liquid must be depressed about o. The liquid does not wet the wall.

Whether, then, a liquid will rise against a solid wall or be depressed by it will depend only on the relative strengths of the adhesion of the wall for the liquid and the cohesion of the liquid for itself. Since mercury does not wet glass, we know that cohesion is here relatively strong, and we should therefore expect that the mercury would be depressed near a glass wall, or within a glass tube, as, indeed, we find it to be. The fact that water will wet glass indicates that in this case adhesion

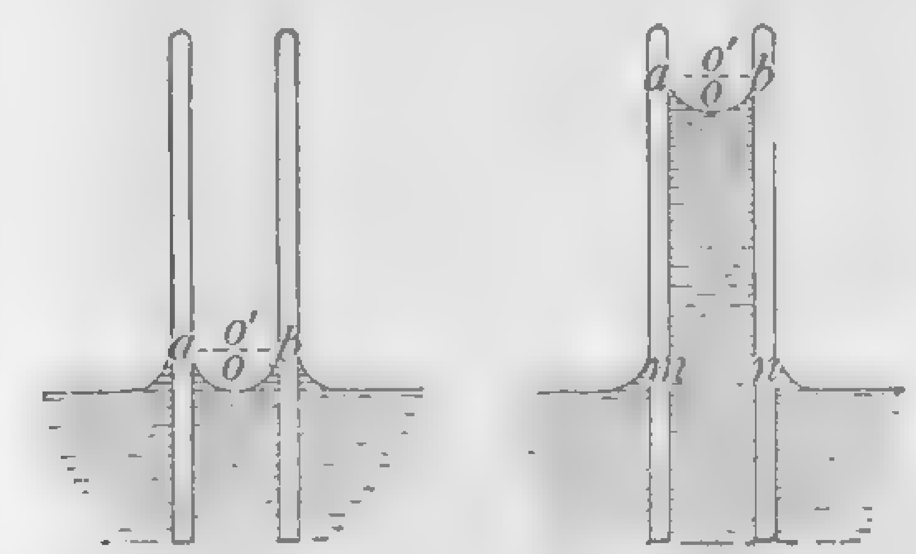


FIG. 102 FIG. 103

A concave meniscus causes a rise in a capillary tube

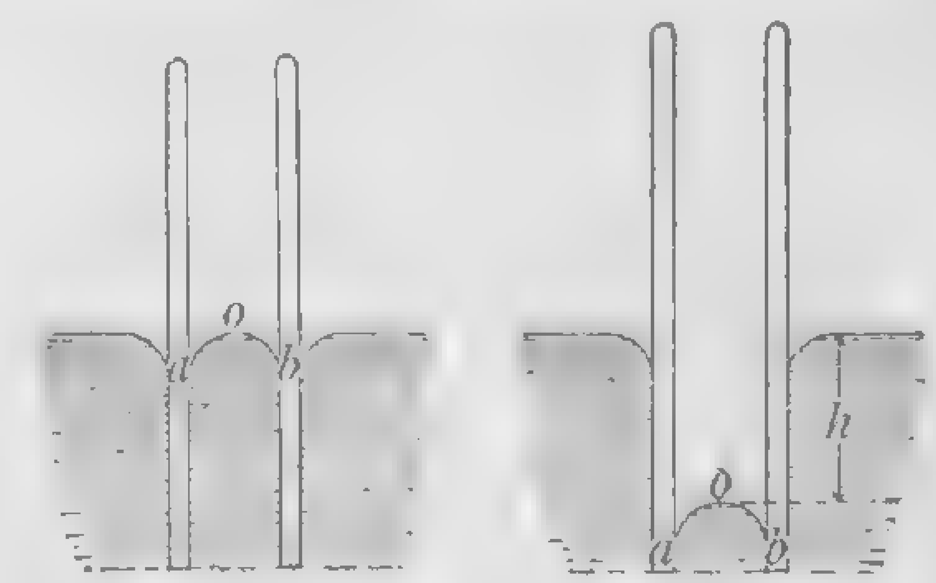


FIG. 104 FIG. 105

A convex meniscus causes a fall in a capillary tube

is relatively strong, and hence we should expect water to rise against the walls of the containing vessel, as in fact it does.

It is clear that a liquid which is depressed near the edge of a vertical solid wall must assume within a tube a surface which is *convex upward*, whereas a liquid which rises against a wall must within such a tube be *concave upward*.

119. Explanation of ascension and depression in capillary tubes. As soon as the curvatures just mentioned are produced, the concave surface aob (Fig. 102) tends, by virtue of surface tension, to straighten out into the flat surface $ao'b$. But it no sooner thus begins to straighten out than adhesion again elevates it at the edges. It will be seen, therefore, that the liquid must continue to rise in the tube until the weight of the volume of liquid lifted, namely $amnb$ (Fig. 103), balances the tendency of the surface aob to flatten out. That

the liquid will rise higher in a small tube than in a large one is to be expected, since the weight of the column of liquid to be supported in the small tube is less.

The convex mercury surface *aob* (Fig. 104) falls until the upward pressure at *o*, due to the depth *h* of mercury (Fig. 105), balances the tendency of the surface *aob* to flatten.

120. Capillary phenomena in everyday life. Capillary phenomena play a very important part in the processes of nature and of everyday life. Thus the rise of oil in wicks of lamps, the complete wetting of a towel when one end of it is allowed to stand in a basin of water, the rapid absorption of liquid by a lump of sugar when only one corner of it is immersed, the taking up of ink by blotting paper, are all illustrations of precisely the same phenomena which we observe in the capillary tubes of Fig. 97.

121. Floating of small objects on water. From a *flat* and *thin* piece of sheet iron cut a circle from 5 to 6 in. in diameter. Place it carefully on the surface of water. In spite of the fact that iron is nearly eight times as dense as water, it will be found to float (Fig. 106). See how many pennies you can pile gently on the center of the disk before you sink it.

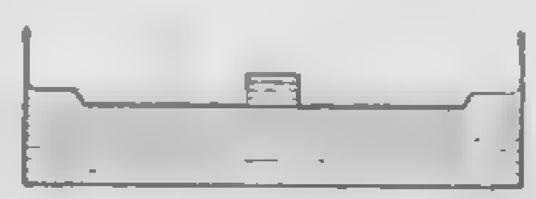


FIG. 106. Cross section of a floating iron disk loaded with pennies

FIG. 107. Cross section of a floating needle

By use of a bent hairpin or a wire float a needle (Fig. 107). If the needle has been previously magnetized, it may be made to move about in any direction over the surface in obedience to the pull of a magnet held, for example, underneath the table.

To discover the cause of this apparently impossible phenomenon, examine closely the surface of the water in the immediate neighborhood of the disk or needle. It will be found to be depressed in the manner shown in Figs. 106 and 107. This furnishes at once the explanation. So long as the needle is so small that its own weight is no greater than the upward force exerted upon it by the tendency of the depressed

(and therefore concave) liquid surface to straighten out into a flat surface, the needle cannot sink in the liquid, no matter how great its density. If the water had wet the needle, that is, if it had risen about the needle instead of being depressed, the tendency of the liquid surface to flatten out would have pulled it down into the liquid instead of forcing it upward. Any body about which a liquid is depressed will therefore float on the surface of the liquid if its mass is not too great. Even if the liquid tends to rise about a body when it is perfectly clean, an imperceptible film of oil upon the body will cause it to depress the liquid, and hence to float.

FIG. 108. Insect walking on the surface of water

The preceding experiment explains the familiar phenomenon of insects walking and running on the surface of water (Fig. 108) in apparent contradiction to the law of Archimedes, in accordance with which they should sink until they displace their own weight of the liquid.

SUMMARY. **Cohesive forces within a free liquid tend to make it assume that form which has the minimum area for a given volume; namely, a sphere. For this reason a liquid film acts like a stretched membrane.**

A liquid wets a solid when at the point of contact of their two free surfaces the force of cohesion between the molecules of the liquid on the one hand and the force of adhesion between the molecules of the solid and the liquid on the other hand gives a resultant whose direction lies within the solid.

A liquid does not wet a solid when, under the forces mentioned above, the direction of the resultant lies within the liquid.

The laws pertaining to capillary tubes are given in § 117.

QUESTIONS AND PROBLEMS

1. The leads for pencils are made by subjecting powdered graphite to enormous pressures produced by hydraulic machines. Explain how the pressure changes the powder to a coherent mass.

2. Explain the watering of flowers by setting the pot in a basin of water.

3. Why will a piece of sharp-cornered glass become rounded when heated to redness in a Bunsen flame?

4. Shot are made by pouring molten lead through a sieve on top of a tall tower and catching it in water at the bottom. Why are the shot spherical?

5. Why does a small stream of water break up into drops instead of falling as a continuous thread?

6. Why does a new and oily steel pen not write well? Why is it difficult to write on oiled paper?

7. Candle grease may be removed from clothing by covering it with blotting paper and then passing a hot flatiron over the paper. Explain.

8. Explain how capillary attraction makes an irrigation system successful.

9. What force is mainly responsible for the return to the surface of the earth of water that has gravitated into the soil? Would the looseness of the soil make any difference in the amount of water which comes to the surface and evaporates? (Dry farming.)

10. Give four common illustrations of capillary attraction.

Absorption of Gases by Solids and Liquids

122. Absorption of gases by solids. Let a large test tube be filled with ammonia gas by heating aqua ammonia and causing the evolved gas to displace mercury in the tube, as in Fig. 109. Let a piece of charcoal an inch long and nearly as wide as the tube be heated to redness and then plunged beneath the mercury. When it is cool, let it be slipped underneath the mouth of the test tube and allowed to rise into the gas. The mercury will be seen to rise in the tube, as in Fig. 110. Why?

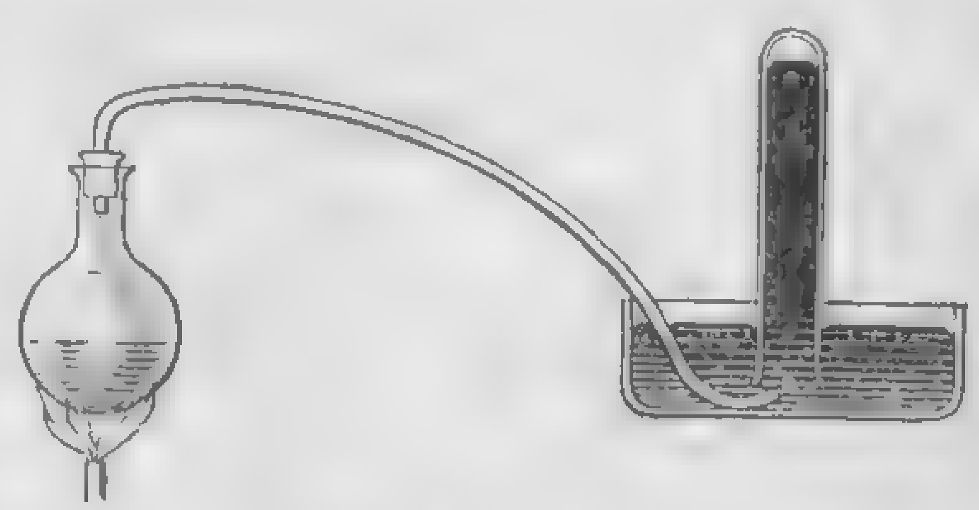


FIG. 109. Filling tube with ammonia

This property of absorbing gases is possessed to a notable degree by porous substances, especially coconut and peach-pit charcoal. It has recently been finding large commercial

application in the condensation of the volatile gases from oil wells into gasoline. Many solids hold, closely adhering to their surfaces, thin layers of the gases with which they are in contact; so that the prominence of the phenomena of absorption in porous substances is probably due primarily to the great extent of surface possessed by such substances.

That the same substance exerts widely different attractions upon the molecules of different gases is shown by the fact that charcoal will absorb 90 times its own volume of ammonia gas, 35 times its volume of carbon dioxide, and only 1.7 times its volume of hydrogen. The usefulness of charcoal as a deodorizer is due to its enormous ability to absorb certain kinds of gases. This property makes it available for use in gas masks. The metal palladium when heated in hydrogen can absorb 800 times its own volume.

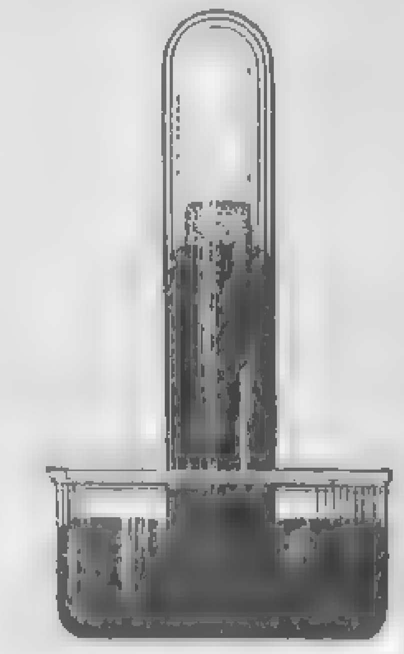


FIG. 110. Absorption of ammonia gas by charcoal

123. Absorption of gases in liquids. Let a beaker containing cold water be slowly heated. Small bubbles of air will be seen to collect in great numbers upon the walls and to rise through the liquid to the surface. That they are bubbles of air and not of steam is proved, first, by the fact that they appear when the temperature is far below boiling and, secondly, by the fact that they do not condense as they rise into the higher and cooler layers of the water.

The experiment shows two things: first, that water ordinarily contains considerable quantities of air dissolved in it, and, secondly, that the amount of air thus dissolved decreases as the temperature rises. The first point is also proved by the existence of fish life, for fishes obtain from the dissolved air the oxygen needed to support life.

The amount of gas absorbed by water varies greatly with the nature of the gas. At 0° C. and a pressure of 76 centimeters 1 cubic centimeter of water will absorb 1050 cubic centimeters of ammonia, 1.8 cubic centimeters of carbon

dioxide, and only .04 cubic centimeter of oxygen. Commercial aqua ammonia is simply ammonia gas dissolved in water.

The following experiment illustrates the absorption of ammonia by water:

Let the flask F (Fig. 111) and tube b be filled with ammonia by passing a current of the gas in at a and out through b. Then let a be corked up and b thrust into G, a flask nearly filled with water colored slightly red by the addition of litmus and a drop or two of acid. As the ammonia is absorbed, the water will slowly rise in b, and as soon as it reaches F it will rush up very rapidly until the upper flask is nearly full. At the same time the color will change from red to blue because of the action of the ammonia upon the litmus.

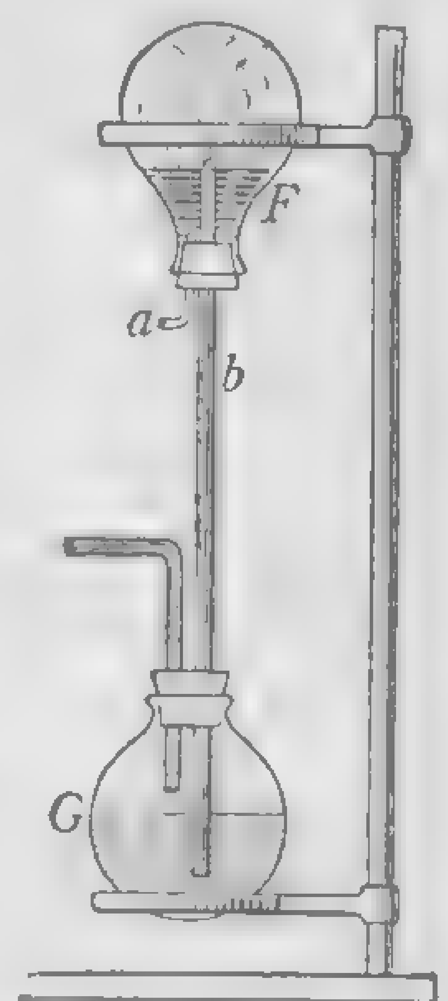


Fig. 111. Absorption of ammonia by water

Experiment shows that *in every case of absorption of a gas by a liquid or a solid the quantity of gas absorbed decreases with an increase in temperature* — a result which was to have been expected from the kinetic theory, since increasing the molecular velocity must of course increase the difficulty of retaining the gaseous molecules.

124. Effect of pressure upon absorption. Soda water is ordinary water in which large quantities of carbon dioxide gas have been absorbed. This impregnation is accomplished by bringing the water into contact with the gas under high pressure. As soon as the pressure is relieved, the gas passes rapidly out of solution. This is the cause of the characteristic effervescence of soda water. These facts show clearly that the amount of carbon dioxide absorbed by water is greater for high pressures than for low. As a matter of fact, careful experiments have shown that the amount of any gas absorbed is directly proportional to the pressure; so that if carbon dioxide under a pressure of 10 atmospheres is brought into contact with water, ten times as much of the gas is absorbed

as if it had been under a pressure of 1 atmosphere. This is known as Henry's law.

Summary. The absorbing power of solids and liquids for gases decreases with increase in temperature.

The quantity of gas absorbed by a liquid is directly proportional to the pressure.

QUESTIONS AND PROBLEMS*

1. In the manufacture of incandescent vacuum lamps why are the glass globes made very hot?

2. Why are bubbles of air seen clinging to the inner surface of a tumbler containing cold water? What difference would a rise in the temperature of the room make in the number and size of the bubbles?

3. Why do fishes in a small aquarium without plants die if the water is not frequently renewed?

* Supplementary questions and problems for Chapter VI are given in the Appendix.

CHAPTER VII

WORK AND MECHANICAL ENERGY *

Definition and Measurement of Work

125. Definition of work. Whenever a force *moves* a body on which it acts, it is said to do work upon that body, and the amount of the work accomplished is measured by the product of the force acting and the distance through which it moves the body. Thus, if 1 gram of mass is lifted 1 centimeter in a vertical direction, 1 gram of force has acted, and the distance through which it has moved the body is 1 centimeter. We say, therefore, that the lifting force has accomplished 1 *gram centimeter* of work. If the gram of force had lifted the body upon which it acted through 2 centimeters, the work done would have been 2 gram centimeters; if a force of 3 grams had acted and the body had been lifted through 3 centimeters, the work done would have been 9 gram centimeters; etc. Or, in general, if W represents the work accomplished, F the value of the acting force, and s the distance through which its point of application moves, then *the definition of work is given by the equation*

$$W = F \times s. \tag{1}$$

In the scientific sense no work is ever done unless the force succeeds in *producing motion* in the body on which it acts. A pillar supporting a building does no work; a man tugging

* It is recommended that this chapter be preceded by an experiment in which the student discovers for himself the law of the lever, that is, the principle of moments (see, for example, Experiment 15 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis), and that it be accompanied by a study of the principle of work as exemplified in at least one of the other simple machines (see, for example, Experiment 17 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis).

at a stone but failing to move it does no work. In the popular sense we sometimes say that we are doing work when we are simply holding a weight or doing anything else which results in fatigue; but in physics the word "work" is used to describe not the effort put forth but the *effect accomplished*, as represented in equation (1).

126. Units of work. There are two common units of work in the metric system: the *gram centimeter* and the *kilogram meter*. As the names imply, the gram centimeter is the work done by a force of 1 gram when it moves the point on which it acts 1 centimeter. The kilogram meter is the work done by a kilogram of force when it moves the point on which it acts 1 meter. The *gram meter* also is sometimes used.

Corresponding to the English unit of force, the pound, is the unit of work, the *foot pound*. This is the work done by a "pound of force" when it moves the point on which it acts 1 foot. Thus, it takes a foot pound of work to lift a pound of mass 1 foot high.

In the absolute system of units the dyne is the unit of force, and the dyne centimeter, or *erg*, is the corresponding unit of work. The erg is the amount of work done by a force of 1 dyne when it moves the point on which it acts 1 cm. To raise 1 l. of water from the floor to a table 1 m. high would require $1000 \times 980 \times 100 = 98{,}000{,}000$ ergs of work. It will be seen, therefore, that the erg is an exceedingly small unit. For this reason it is customary to employ a unit which is equal to 10,000,000 ergs. It is called a *joule* in honor of the great English physicist James Prescott Joule (1818–1889). The work done in lifting a liter of water 1 m. is therefore 9.8 joules.

Summary. Work = force times distance; that is, $W = F \times s$.

Gravitational units of work are the gram centimeter (g. cm.), the gram meter (g. m.), the kilogram meter (kg. m.), the foot pound (ft. lb.), and the foot ton (ft. t.).

Absolute units of work are the dyne centimeter, or erg, and the joule (= 10,000,000 ergs).

QUESTIONS AND PROBLEMS

1. A carpenter pushed 5 lb. on his plane while taking off a shaving 4 ft. long. How much work was done?

2. A woman in sweeping a rug moved the nozzle of a vacuum cleaner a total distance of 130 ft., using an average force of one-half pound. How much work did she do?

3. To drag a trunk weighing 120 lb. required a force of 40 lb. How much work would be required to drag this trunk 2 yd.? to lift it 2 yd. vertically?

4. A horse pulls a metric ton of coal to the top of a hill 30 m. high. Express the work accomplished in kilogram meters (a metric ton = 1000 kg.).

5. A certain powerful machine exerted an average force of 36 t. in punching rivet holes in a sheet of steel 1 in. thick. Calculate the number of foot tons of work done in punching one hole; the number of foot pounds of work.

6. Why is less work done in stretching a steel rod to a tension of 2000 lb. than in stretching a coiled spring to the same tension? Does the same reasoning which applies to this question prove that it is safer to test a boiler with water than with compressed air? Explain.

WORK EXPENDED UPON AND ACCOMPLISHED BY SYSTEMS OF PULLEYS

127. The single fixed pulley. Let the force of the earth's attraction upon a mass R be overcome by pulling upon a spring balance S, in the manner shown in Fig. 112, until R moves slowly upward. If R is 100 g., the spring balance will also be found to register a force of 100 g., if there is no friction in the pulley.

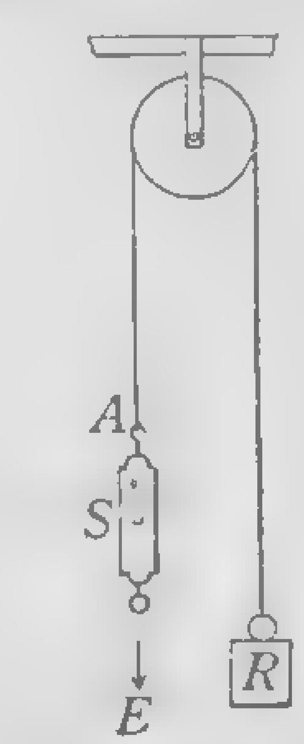


FIG. 112. The single fixed pulley

This experiment shows that in the use of the single fixed pulley the acting force, or effort, E, producing the motion, is equal to the resisting force, or resistance, R, opposing the motion.

Again, since the length of the string is always constant, the distance s through which

the point A, at which E is applied, must move is always equal to the distance s' through which the weight R is lifted. Hence, if we consider the work put into the system at A, namely, $E \times s$, and the work accomplished by the system at R, namely, $R \times s'$, we find, obviously, since $R = E$ and $s = s'$, that

$$E \times s = R \times s'; \tag{2}$$

that is, in the case of the single fixed pulley *the work done by the acting force E (the effort) is equal to the work done against the resisting force R (the resistance)*, or the work *put into* the machine at A is equal to the work *accomplished by* the machine at R.

128. The single movable pulley. Now let the force of the earth's attraction upon the mass R be overcome by a single movable pulley, as shown in Fig. 113. Since the weight of R (R representing in this case the weight of both pulley and suspended mass) is now supported half by the strand C and half by the strand B, the force E acting at A to hold the weight in place, or to move it slowly upward if there is no friction, should be only half of R. A reading of the balance will show that this is the case when due allowance is made for the weight of the pulley.

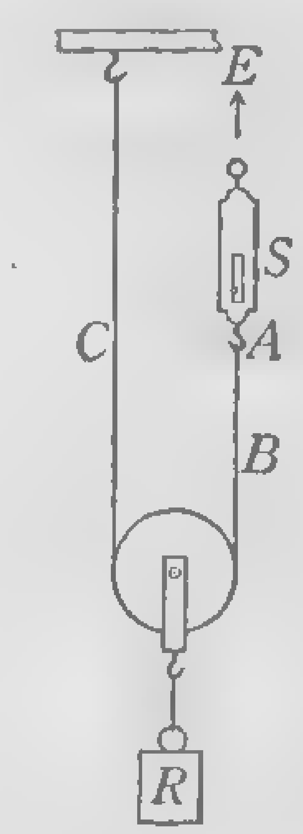


FIG. 113. The single movable pulley

Experiment thus shows that *in the case of the single movable pulley the effort E is just half as great as the resistance R.*

But when we again consider the *work* which the force E must do to lift the weight R a distance s', we see that A must move upward 2 inches in order to raise R 1 inch; for when R moves up 1 inch, both the strands B and C must be shortened 1 inch. As in the case of the fixed pulley, therefore, since $R = 2\,E$ and $s' = \frac{1}{2}\,s$,

$$E \times s = R \times s';$$

that is, in the case of the single movable pulley also *the work put into the machine by the effort E is equal to the work accomplished by the machine against the resistance R.*

129. Combination of pulleys. Let a weight R be lifted by means of such a system of pulleys as is shown in Fig. 114, either (1) or (2). Here, since R is supported by 6 strands of the cord, it is clear that the force which must be applied at A to hold R in place, or to make it move slowly upward if there is no friction, should be but $\frac{1}{6}$ of R.

The experiment will show this to be the case if the effects of friction, often very considerable, are eliminated by taking the mean of the forces which must be applied at E to cause it to move first slowly upward and then slowly downward. The law of any combination of movable pulleys may then be stated thus: *If n represents the number of strands between which the weight is divided,*

$$\frac{R}{E} = n. \qquad (3)$$

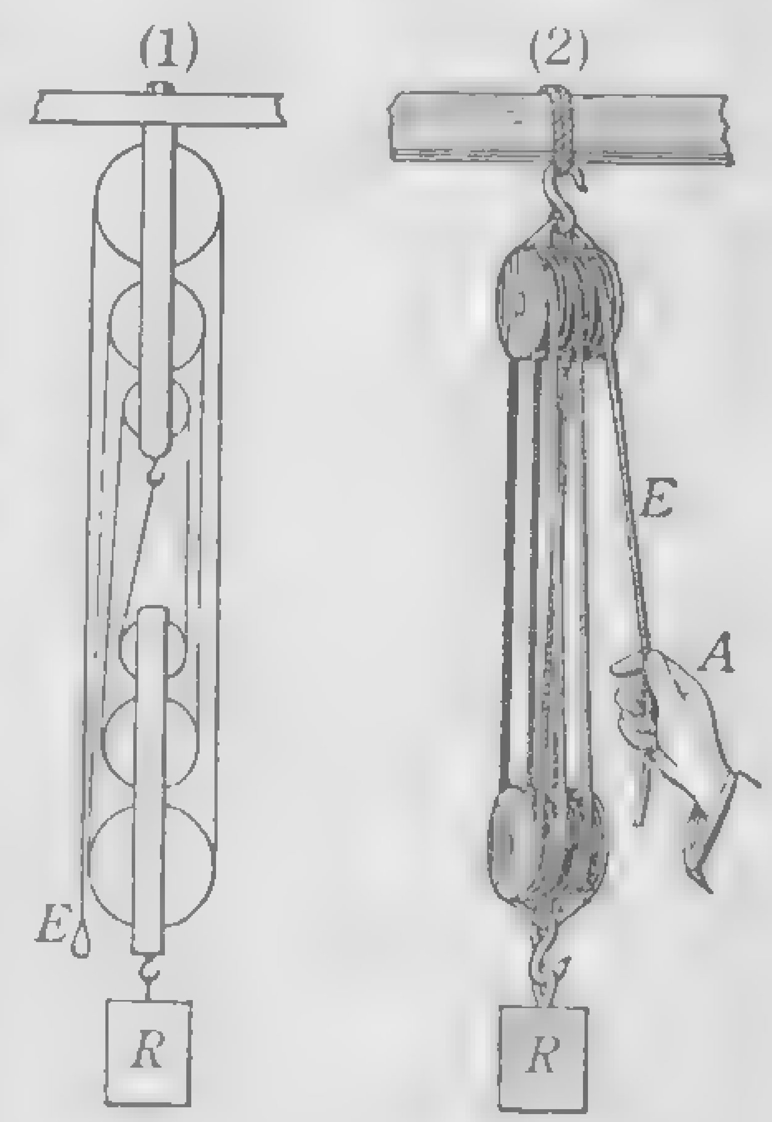


FIG. 114. Combinations of pulleys

But when we again consider the work which the force E must do to lift the weight R through a distance s', we see that, in order that the weight R may be moved up through 1 inch, each of the strands must be shortened 1 inch, and hence the point A must move through n inches; that is, $s' = s/n$. Hence, ignoring friction, in this case also we have

$$E \times s = R \times s';$$

that is, although the effort E is only $1/n$ of the resistance R, *the work put into the machine by the effort E is equal to the work accomplished by the machine against the resistance R.*

130. Mechanical advantage. The preceding experiments show that by applying a small force E it is sometimes possible to overcome a much larger resisting force R. *The ratio of the resistance R to the effort E (ignoring friction) is called the*

mechanical advantage of the machine. Thus, the mechanical advantage of the single fixed pulley is 1, that of the single movable pulley is 2, that of the system of pulleys shown in Fig. 114 is 6, etc.

If the acting force is applied at R instead of at E, the mechanical advantage of the systems of pulleys of Fig. 114 is $\frac{1}{6}$, for it requires an application of 6 pounds at R to lift 1 pound at E. But it will be observed that the resisting force at E now moves six times as fast and six times as far as the acting force at R. *We can thus either sacrifice speed to gain force or sacrifice force to gain speed,* but in every case whatever we gain in the one we lose in the other. Thus, in the hydraulic elevator shown in Fig. 16 (p. 20) the cage moves only as fast as the piston, but in that shown in Fig. 17 it moves four times as fast. Hence the force applied to the piston in the latter case must be four times as great as in the former if the same load is to be lifted. This means that the diameter of the latter cylinder must be twice as great.

SUMMARY. In ideal frictionless pulley systems the work expended on the system by the effort E equals the work accomplished by the system against the resistance R.

The mechanical advantage of any machine is the ratio of the resistance R to the effort E when friction is ignored.

If R is greater than E, speed is lost to gain force; if R is less than E, force is lost to gain speed.

The mechanical advantage of a pulley system using one continuous rope equals the number of strands between which the weight is divided (usually 1 less than the total number of strands); that is,

$$\frac{R}{E} = n.$$

QUESTIONS AND PROBLEMS

1. Two men, pulling 50 lb. each, lifted 300 lb. by a system of pulleys. Assuming no friction, how many feet of rope did they pull down in raising the weight 20 ft.?

2. The fixed pulley (*mechanical advantage = 1*) is extensively used in connection with clotheslines, awnings, and flags. Explain.

3. (1) Represent by a diagram a system of pulleys consisting of a double fixed block and a single movable block. (2) How great a weight can be balanced by a force of 30 lb. applied to the free end of the rope?

4. A piano was hoisted by means of a movable block having two pulleys and a fixed block having three pulleys. (1) Represent by a diagram the system of pulleys. (2) What is the mechanical advantage of the system?

Work and the Lever

131. The law of the lever. The lever is a rigid rod free to turn about some point P called the *fulcrum* (Fig. 115).

First let a meter stick be balanced as in the figure, and then let a mass of, say, 300 g. be hung by a thread from a point 15 cm. from the fulcrum. Then let a point be found on the other side of the fulcrum at which a weight of 100 g. will just balance the 300 g. This point will be found to be 45 cm. from the fulcrum. It will be seen at once that the product of 300 × 15 is equal to the product of 100 × 45.

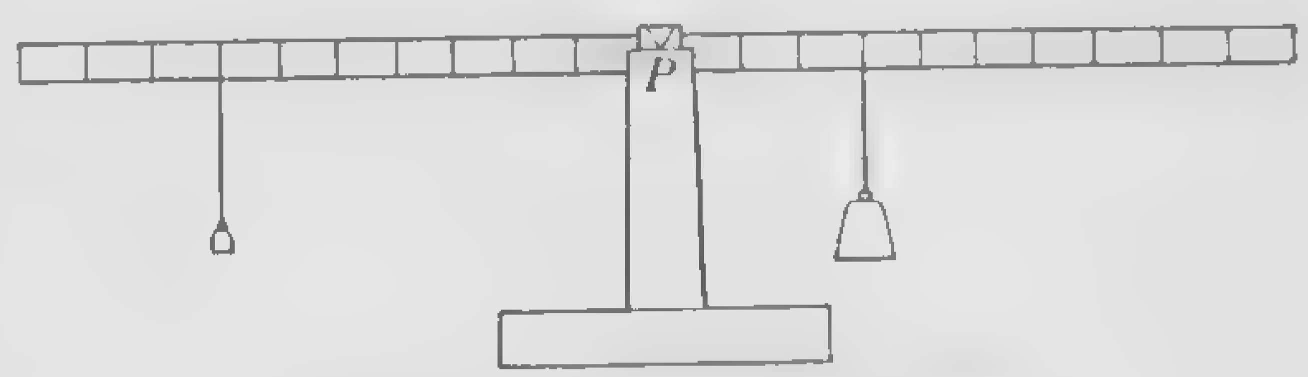


Fig. 115. The single lever

Next let the point be found at which 150 g. just balance the 300 g. This will be found to be 30 cm. from the fulcrum. Again, the products 300 × 15 and 150 × 30 are equal.

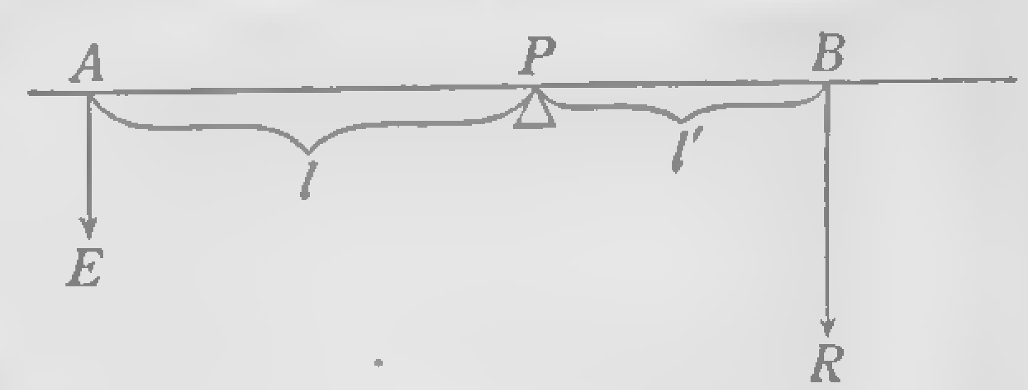
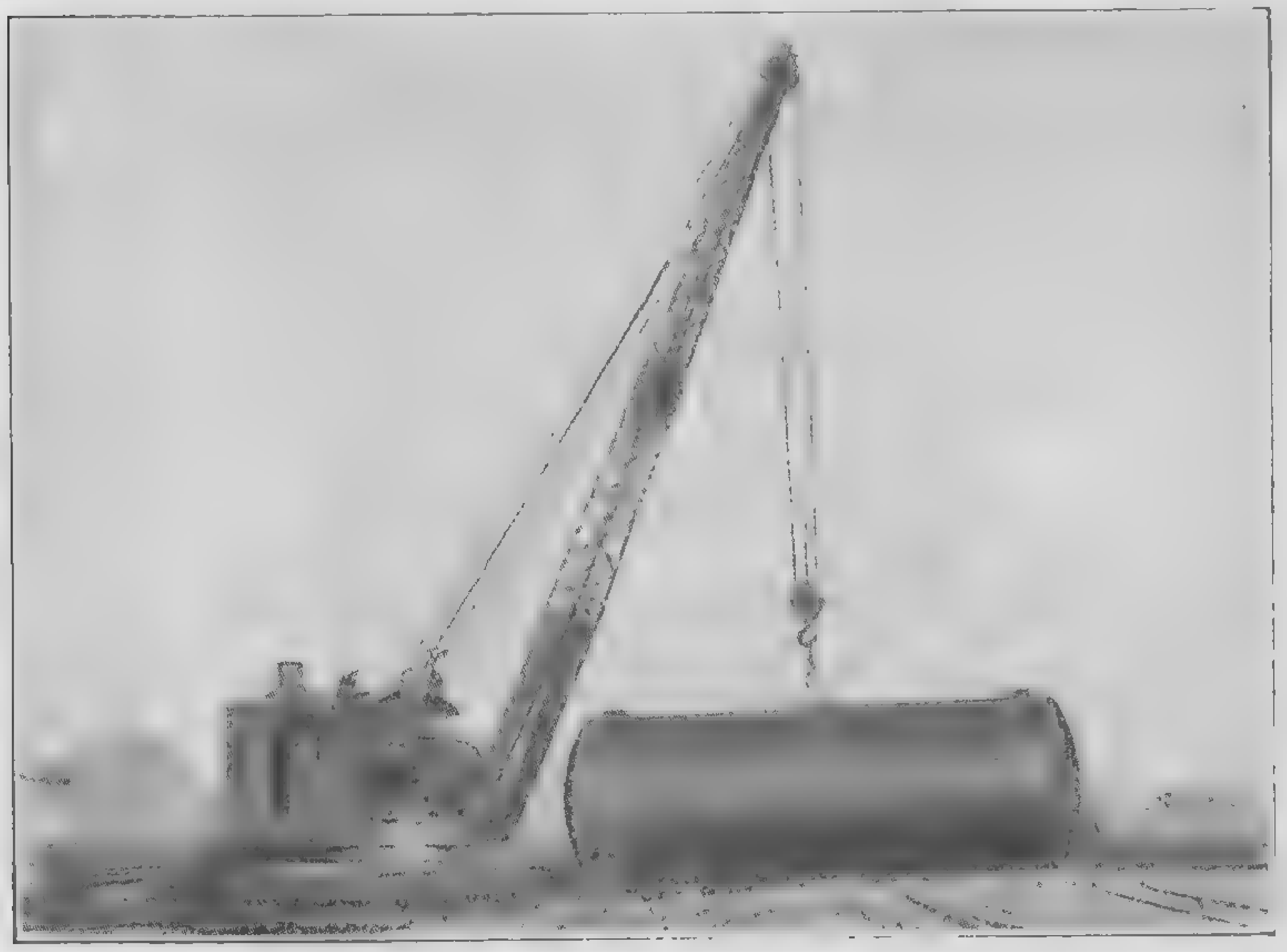


Fig. 116. Illustrating the law of moments, namely, $El = Rl'$

No matter where the weights are placed or what weights are used on either side of the fulcrum, if the lever is balanced the product of the effort E by its distance l from the fulcrum (Fig. 116) will be found to be equal to the product of the resistance R by its distance l' from the fulcrum.

AN ELECTRIC SHOVEL

A giant electric shovel, the most human of machines; it digs like a Titan and is used for all kinds of excavating; it is simply a combination of levers and pulleys. The picture shows the largest shovel in the world. The dipper has a capacity of 8 cubic yards (= 10 tons of coal). (Courtesy of the Marion Shovel Company)



LOCOMOTIVE CRANES

Locomotive cranes — again merely combinations of levers and pulleys. The upper one is the world's largest wrecking crane; it can be operated by one man; it can lift more than 200 tons; it replaces a crew of 50 men; it is shown here hoisting another locomotive crane. (Courtesy of the Orton Crane and Shovel Company)

Now the perpendicular distances l and l' from the fulcrum to the line of action of the forces are called the *lever arms* of the forces E and R, and the product of a force by its lever arm is called the *moment* of that force (Fig. 117). These experiments on the lever may then be generalized in the following law: *The moment of the effort is equal to the moment of the resistance.* Algebraically stated, it is

$$El = Rl'. \tag{4}$$

It will be seen that the *mechanical advantage* of the lever, namely R/E, is equal to l/l'; that is, to *the lever arm of the effort divided by the lever arm of the resistance.*

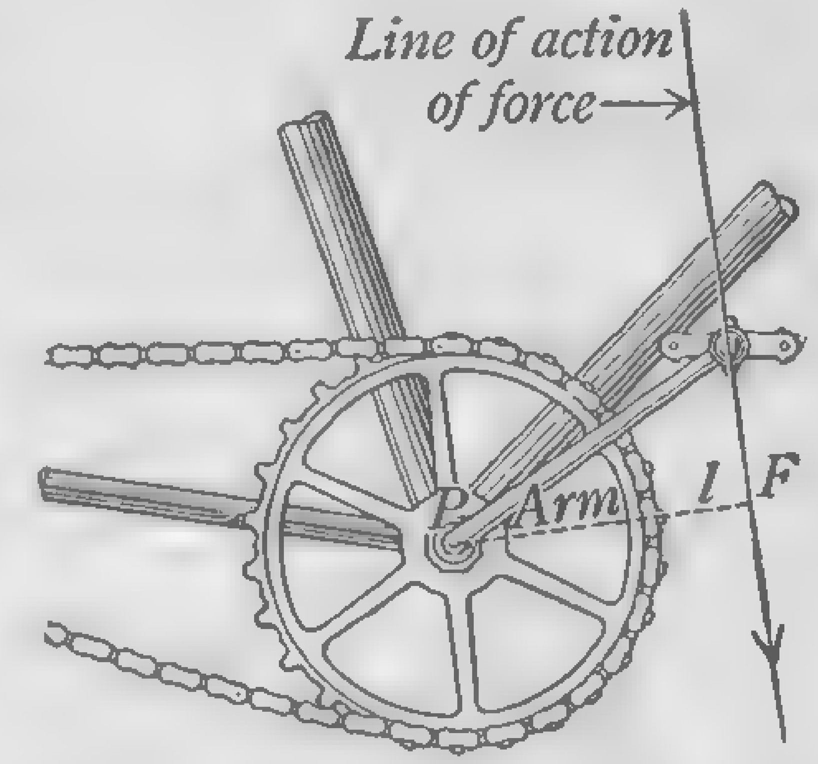


FIG. 117. The moment of the force of the rider's foot is the force times the arm, $F \times l$

132. General laws of the lever. If parallel forces are applied at several points on a lever, as in Figs. 118 and 119, it will be found, in the particular cases illustrated, that for equilibrium

$$200 \times 30 = 100 \times 20 + 100 \times 40,$$

and $300 \times 20 + 50 \times 40 = 100 \times 15 + 200 \times 32.5$;

that is, *the sum of all the moments which are tending to turn the lever in one direction about any axis is equal to the sum of all the moments tending to turn it in the opposite direction.*

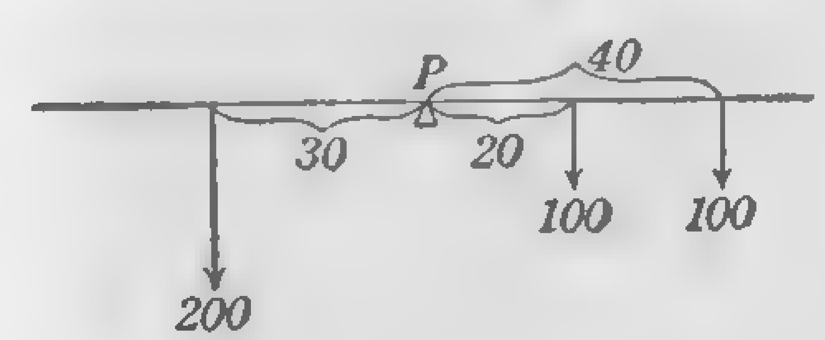


FIG. 118

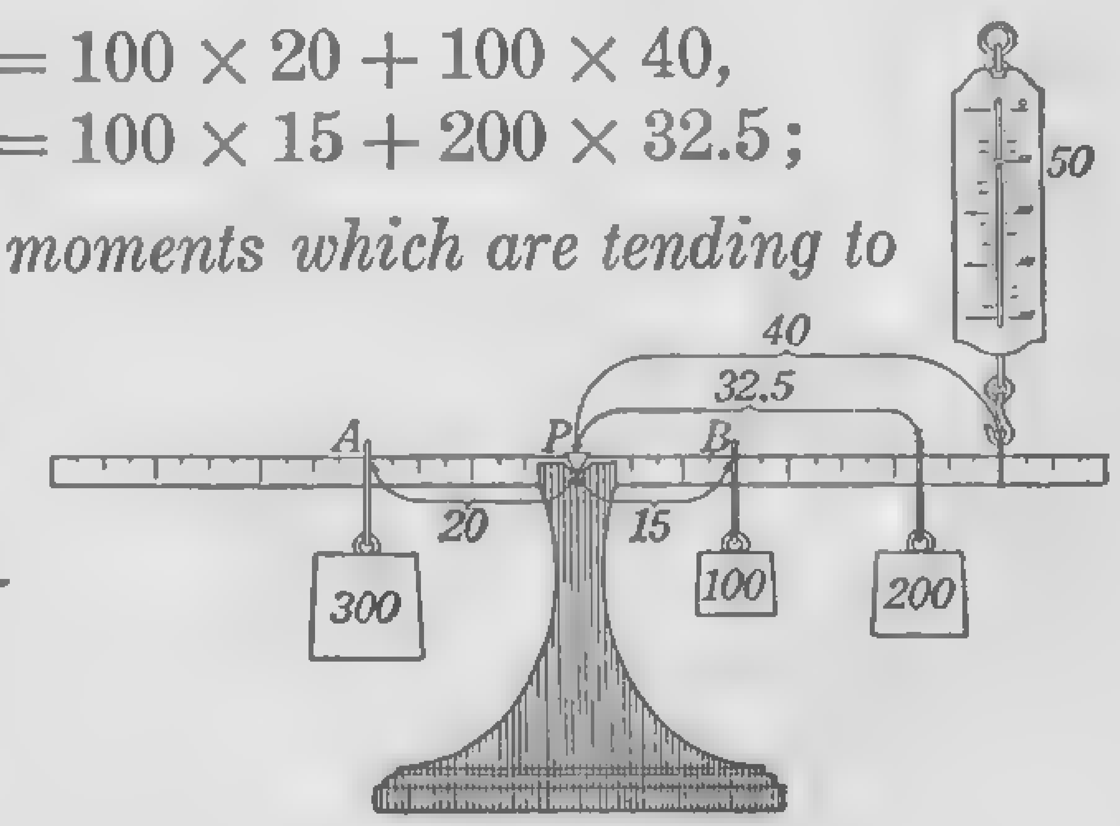


FIG. 119

Condition of equilibrium of a bar acted upon by several forces

If, further, we support the levers of Figs. 118 and 119 by spring balances attached at P, we shall find, after allowing for the weight of the stick, that the two forces indicated by the balances are, respectively, $200 + 100 + 100 = 400$ and $300 + 100 + 200 - 50 = 550$; that is, *the sum of all the forces acting in one direction on the lever is equal to the sum of all the forces acting in the opposite direction.*

133. The couple. There is one case in which parallel forces can have no single force as their resultant; namely, the case represented in Fig. 120. Such *a pair of equal and opposite forces acting at different points on a lever is called a couple* and can be neutralized only by another couple tending to produce rotation in the opposite direction. The moment of such a couple is evidently $F_1 \times oa + F_2 \times ob = F_1 \times ab$; that is, it is one of the forces times the total distance between them.

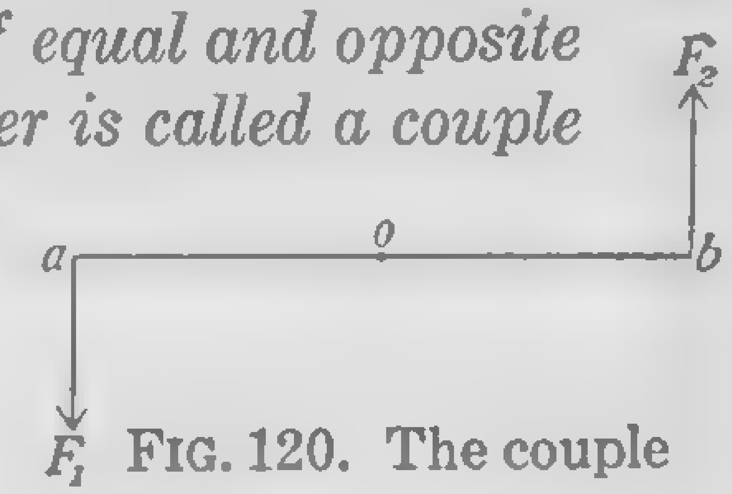


FIG. 120. The couple

134. Work expended upon and accomplished by the lever. We have just seen that when the lever is in equilibrium — that is, when it is *at rest* or is *moving uniformly* — the relation between the effort E and the resistance R is shown in the equation of moments; namely $El = Rl'$. Let us now suppose, precisely as in the case of the pulleys, that the force E raises the weight R through a small distance s'. To accomplish this the point A to which E is attached must move through a distance s (Fig. 121). From the similarity of the triangles APn and BPm it will be seen that l/l' is equal to s/s'. Hence equation (4), which represents the law of the lever and which may be written $E/R = l'/l$, may also be written in the form

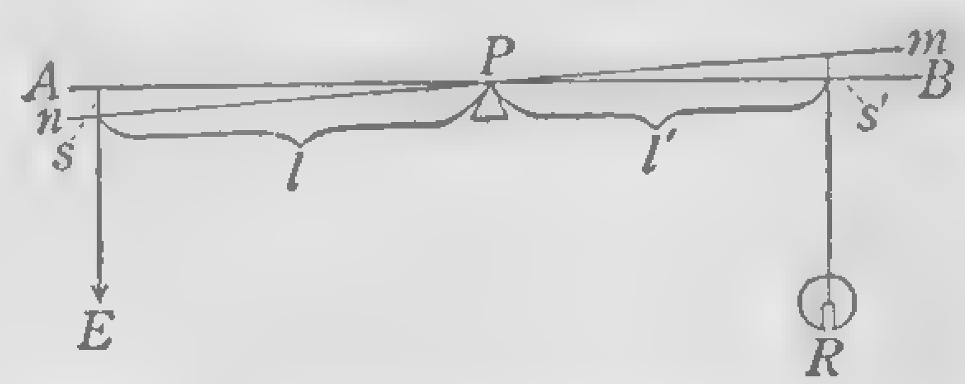


FIG. 121. Showing that the equation of moments, $El = Rl'$, is equivalent to $Es = Rs'$

$$\frac{E}{R} = \frac{s'}{s}, \text{ or } Es = Rs'.$$

Now Es represents the work done by the effort E, and Rs' the work done against the resistance R. Hence the law of moments, which has just been found by experiment to be the law of the lever, is equivalent to the statement that *whenever work is accomplished by the use of the lever, the work expended upon the lever by the effort E is equal to the work accomplished by the lever against the resistance R.*

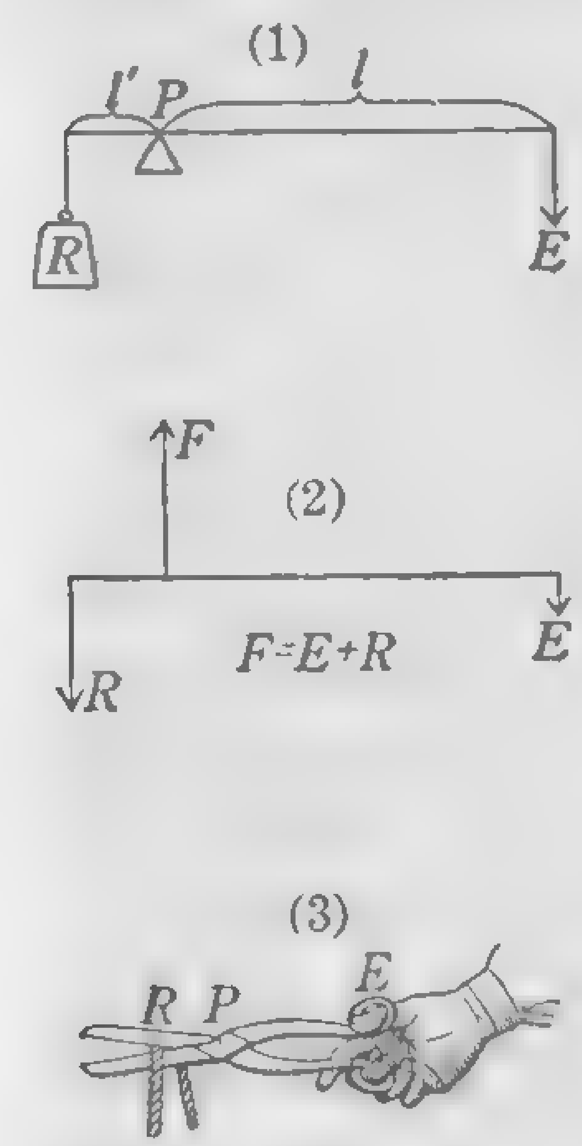


FIG. 122. Levers of first class

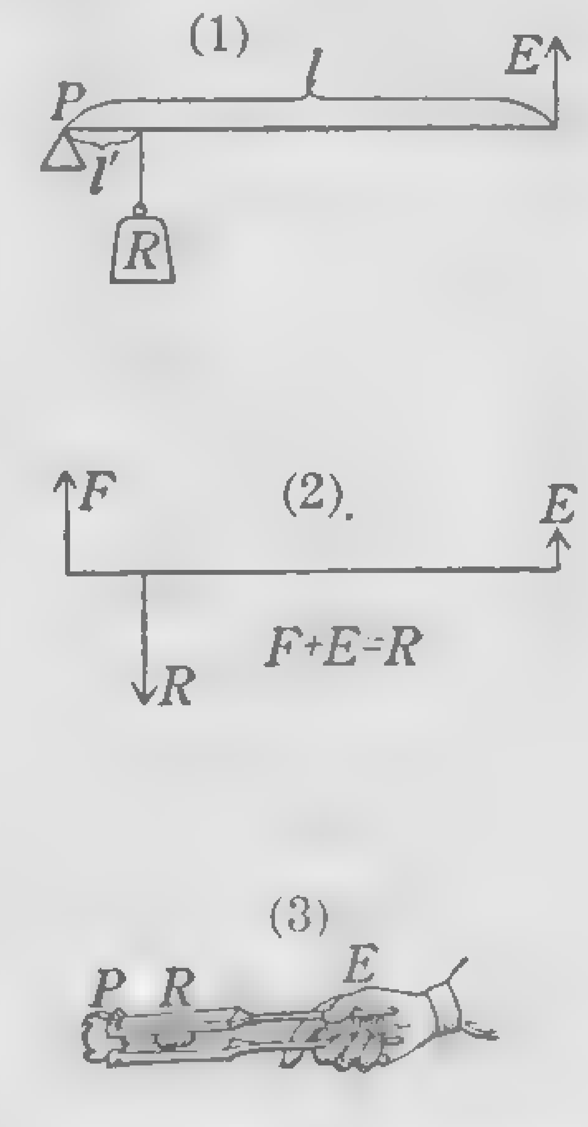


FIG. 123. Levers of second class

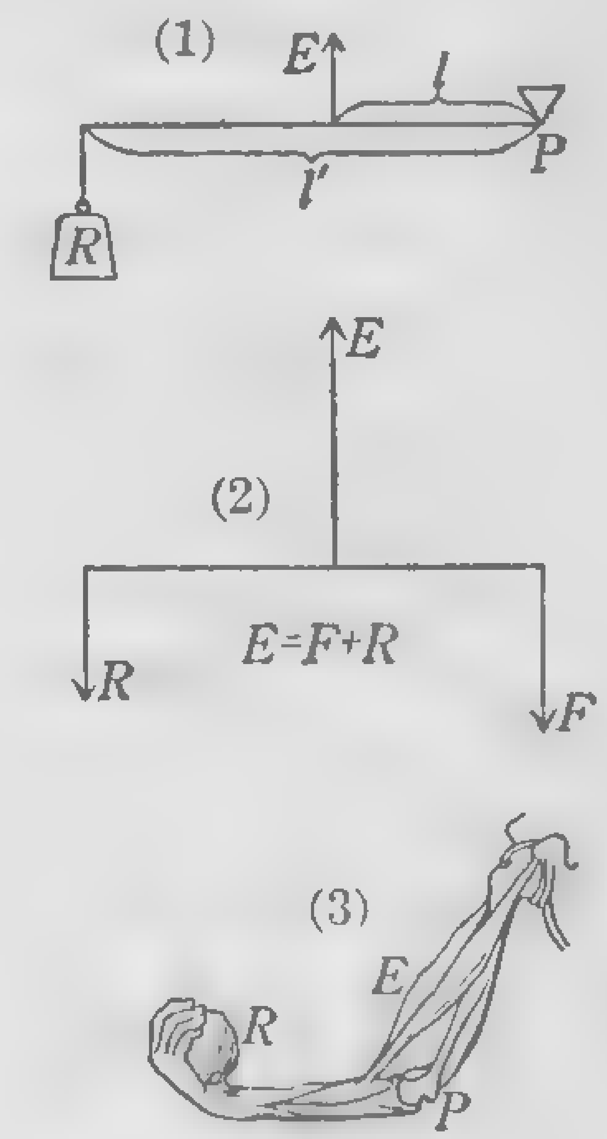


FIG. 124. Levers of third class

135. The three classes of levers. Although the law stated in § 134 applies to all forms of the lever, it is customary to divide them into three classes, as follows:

1. In levers of the first class the fulcrum P is between the acting force E and the resisting force R (Fig. 122). The mechanical advantage of levers of this class is greater or less than unity according as the lever arm l of the effort is greater or less than the lever arm l' of the resistance.

2. In levers of the second class the resistance R is between the effort E and the fulcrum P (Fig. 123). Here the lever arm of the effort, that is, the distance from E to P, is necessarily greater than the lever arm of the resistance, that is, the

distance from R to P. Hence the mechanical advantage of levers of the second class is always greater than 1.

3. In levers of the third class the acting force is between the resisting force and the fulcrum (Fig. 124). The mechanical advantage is then obviously less than 1; that is, in this type of lever force is always sacrificed for the sake of gaining speed.

In all these cases the force F exerted upon the lever by the fulcrum P may be found by the relation stated at the close of § 132.

SUMMARY. The moment of a force is the force times its lever arm. The lever arm is the perpendicular distance from the axis of rotation to the line of action of the force.

Law of the simple lever. The moment of the effort equals the moment of the resistance; that is, $El = Rl'$.

General law of the lever. (1) The sum of all the moments tending to turn the lever in one direction about any axis is equal to the sum of all the moments tending to turn it in the opposite direction; (2) the sum of all the forces acting in one direction on the lever is equal to the sum of all the forces acting in the opposite direction.

In the ideal lever the work expended on the lever by the effort equals the work accomplished by the lever against the resisting force.

A couple consists of a pair of equal and opposite forces acting at different points on a lever. It can be neutralized only by an opposing couple having an equal moment.

QUESTIONS AND PROBLEMS

1. Explain the principle of weighing by the steelyards (Fig. 125). What must be the weight of the bob P if at a distance of 40 cm. from the fulcrum O it balances a weight of 10 kg. placed at a distance of 2 cm. from O?

2. Why do tinners' shears have long handles and short blades and tailors' shears just the opposite?

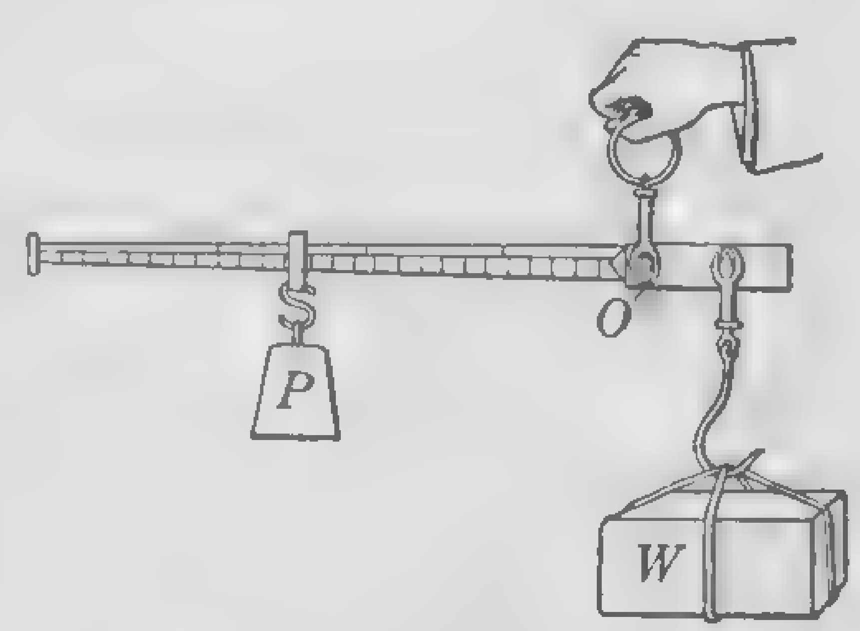


FIG. 125. Steelyards

3. A balance has unequal arms, the left-hand arm having a length 99 per cent of that of the right-hand arm. A dealer has the habit of putting in the left-hand pan the articles which he sells. Who gains, the dealer or the customer? Why?

4. If you knew your own weight, how could you determine the weight of a companion if you had only a teeter board (a seesaw) and a foot rule?

5. Two boys are carrying a bag of walnuts at the middle of a long stick. Will it make any difference whether they walk close to the bag or farther away so long as each is at the same distance?

6. Two boys carry a load of 60 lb. on a pole between them. If the load is 4 ft. from one boy and 6 ft. from the other, how many pounds does each boy carry? (Consider the force exerted by one of the boys as the effort, the load as the resistance, and the second boy as the fulcrum.)

7. Two men lift a small 40-foot telegraph pole weighing 400 lb. The center of gravity of the pole is 16 ft. from one end. How many pounds are supported by each man, assuming that the pole is grasped at its extremities?

8. One end of a piano must be raised to remove a broken caster. The force required is 240 lb. Make a diagram to show how a 6-foot steel bar may be used as a second-class lever to raise the piano with an effort of 40 lb.

9. By a series of diagrams (see Fig. 117) explain how the moment of the force of a bicycle rider's foot passes from zero to a maximum and then to zero at each downward movement, or half-revolution, of his foot.

10. A lever is 3 ft. long. Where must the fulcrum be placed so that a weight of 300 lb. at one end shall be balanced by 50 lb. at the other?

11. A telephone pole 40 ft. long balanced horizontally over a support placed 10 ft. from the thick end. When the support was placed under the pole 15 ft. from the thick end, it balanced when a workman weighing 160 lb. applied his full weight at the small end. Find the weight of the pole.

12. A stick 3 ft. long rests across the shoulder of a man, 1 ft. of its length extending to the rear of the shoulder. On this end hangs a 10-pound bundle. Find the downward force of the hand at the

2-foot end balancing the bundle. Find the force of the shoulder upward against the stick, neglecting the weight of the stick. What would have been the upward force of the shoulder had 2 ft. of the stick extended to the rear?

13. Why is it that a couple cannot be balanced by a single force?

The Principle of Work

136. Statement of the principle of work. The study of pulleys led us to the conclusion that in all cases where such machines are used the work done by the effort is equal to the work done against the resistance, provided always that friction may be neglected and that the motions are uniform so that none of the force exerted is used in overcoming inertia. The study of levers led to precisely the same result. In Chapter II the study of the hyraulic press showed that the same law applied in this case also, for it was shown that the force on the small piston times the distance through which it moved was equal to the force on the large piston times the distance through which it moved. Similar experiments upon all sorts of machines have shown that the following is an absolutely general law: *In all mechanical devices of whatever sort, in all cases where friction may be neglected or eliminated, the work expended upon the machine is equal to the work accomplished by it.*

This important generalization, called *the principle of work,* was first stated by Newton in 1687. It has proved to be one of the most fruitful principles ever put forward in the history of physics. By its application it is easy to deduce the relation between the force applied and the force overcome in any sort of machine, provided only that friction is negligible and that the motions take place slowly. It is only necessary to produce or to imagine a displacement at one end of the machine and then to measure or calculate the corresponding displacement at the other end. The ratio of the second displacement to the first is the ratio of the force acting to the force overcome.

137. The wheel and axle. Let us apply the principle of work to discover the law of the wheel and axle (Figs. 126 and 127). When the large wheel has made one revolution, the point A on the rope moves down a distance equal to the circumference of the wheel. During this time the weight R is lifted a distance equal to the circumference of the axle. Hence the equation $Es = Rs'$ becomes $E \times 2\pi R_w = R \times 2\pi r_a$, where R_w and r_a are the radii of the wheel and axle respectively. This equation may be written in the form

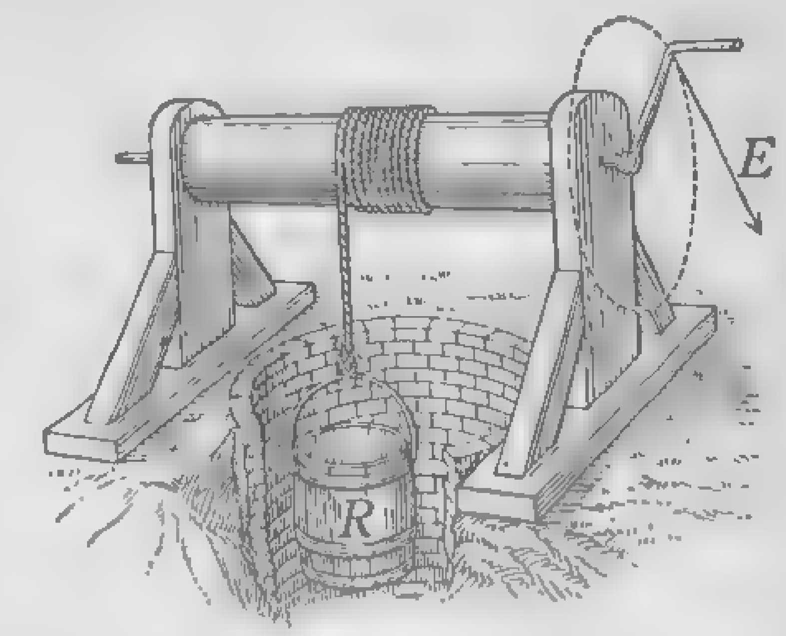


FIG. 126. A well windlass — a form of wheel and axle

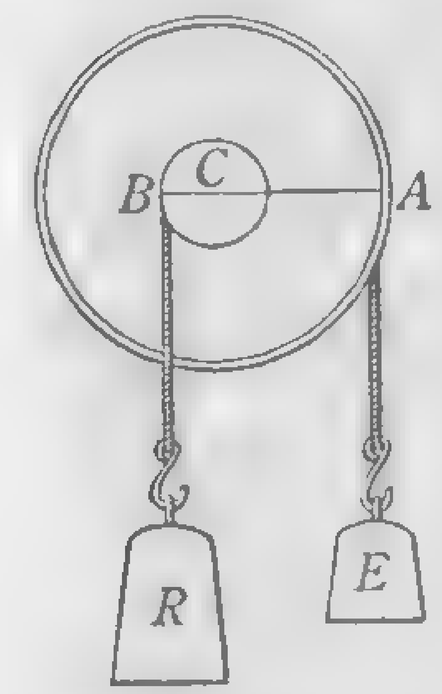


FIG. 127. The wheel and axle

$$\frac{R}{E} = \frac{R_w}{r_a}; \tag{5}$$

that is, *the weight lifted on the axle is as many times the force applied to the wheel as the radius of the wheel is times the radius of the axle.* Otherwise stated, *the mechanical advantage of the wheel and axle is equal to the radius, diameter, or circumference of the wheel divided by the radius, diameter, or circumference of the axle.*

138. The principle of work applied to the inclined plane. The work done against gravity in lifting a weight R (Fig. 128) from the bottom to the top of a plane is evidently equal to R times the height h of the plane. But the work done by the acting force E while the carriage of weight R is being pulled from the bottom to the top of the plane is equal to E times the length l of the plane. Hence the principle of work gives

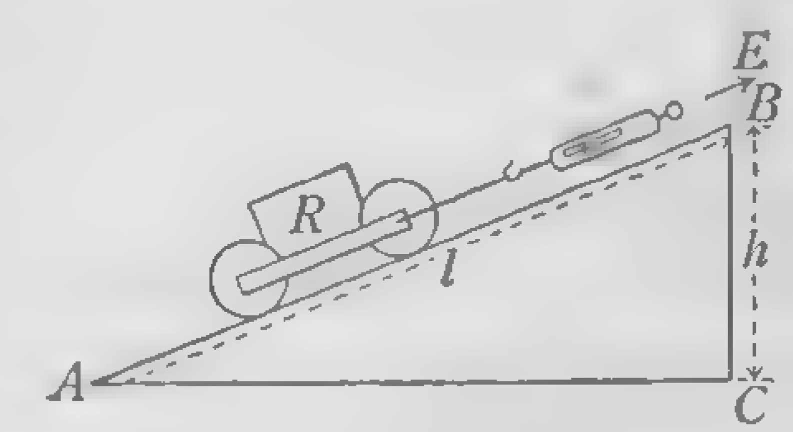


FIG. 128. The inclined plane

$$El = Rh, \text{ or } \frac{R}{E} = \frac{l}{h}; \tag{6}$$

that is, *the mechanical advantage of the inclined plane, or the ratio of the weight lifted to the force acting parallel to the plane, is equal to the ratio of the length of the plane to the height of the plane.* This is precisely the conclusion at which we arrived in another way in Chapter V, p. 68.

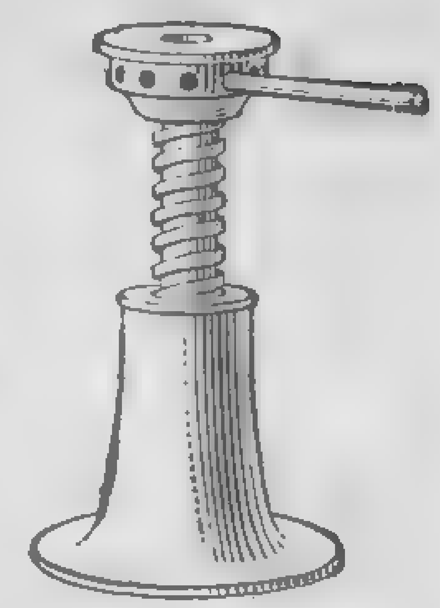


FIG. 129. The jackscrew

139. The screw. The screw (Fig. 129) is a combination of the inclined plane and the lever. Its law is easily obtained from the principle of work. When the force which acts on the end of the lever has moved this point through one complete revolution, the weight R, which rests on top of the screw, has evidently been lifted through a vertical distance equal to the distance between two adjoining threads. This distance d is called the *pitch* of the screw. Hence, if we represent by l the length of the lever, the principle of work gives

$$E \times 2\pi l = Rd, \text{ or}$$

$$\frac{R}{E} = \frac{2\pi l}{d}; \qquad (7)$$

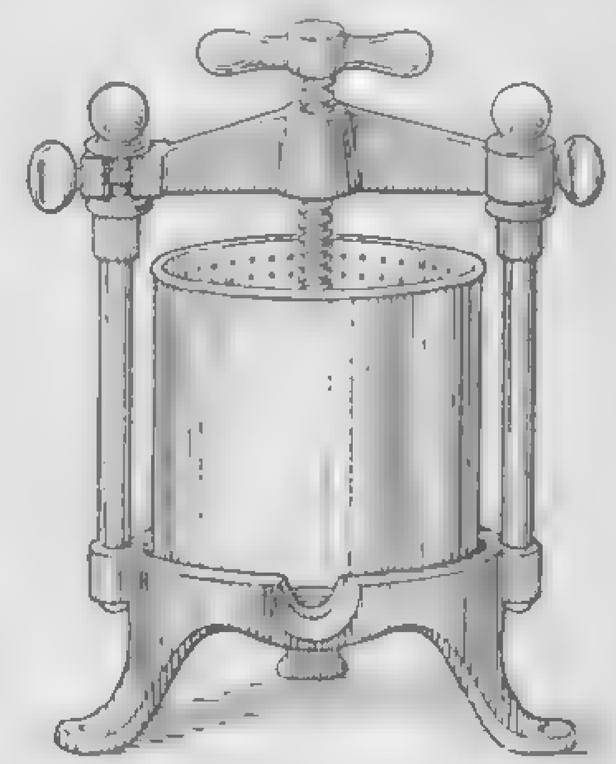


FIG. 130. The fruit-jelly or lard press

that is, *the mechanical advantage of the screw, or the ratio of the weight lifted to the force applied, is equal to the ratio of the circumference of the circle moved over by the end of the lever to the distance between the threads of the screw.* In actual practice the friction in such an arrangement is always very great, so that the effort exerted must always be considerably greater than that given by equation (7). The common jackscrew just described (used chiefly for raising buildings), the turnbuckle, the automobile jack, the lard press (Fig. 130), the micrometer-screw caliper for measuring minute distances, and the vise (Fig. 131) are all familiar forms of the screw.

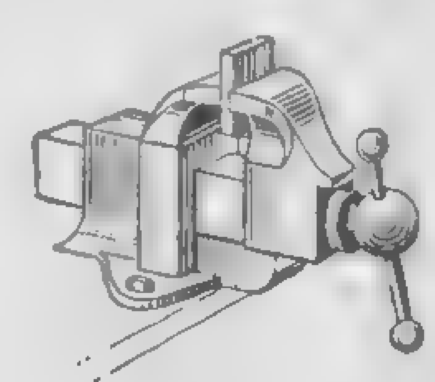


FIG. 131. The vise

140. A train of gear wheels. A form of machine capable of very high mechanical advantage is the train of gear wheels shown in Fig. 132. Let the student show from the principle of work,

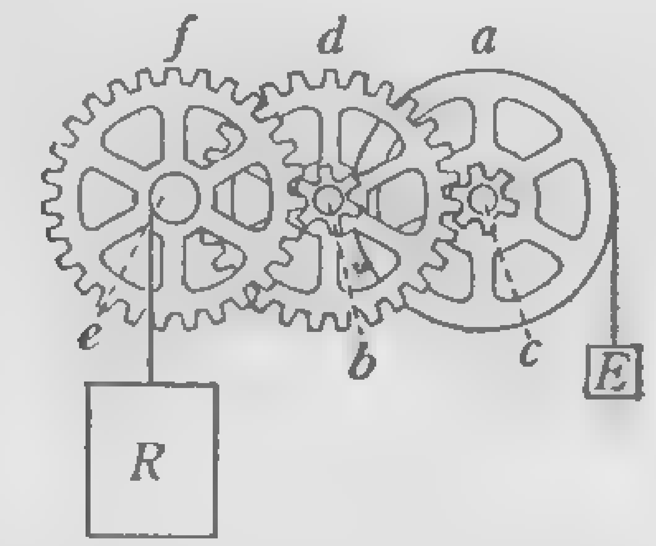


FIG. 132. Train of gear wheels

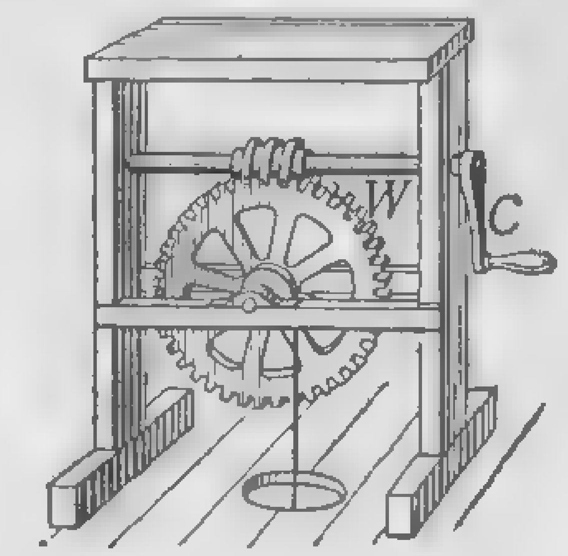


FIG. 133. The worm gear

namely $Es = Rs'$, that the mechanical advantage, that is, R/E, of such a device is

$$\frac{\text{Circumference of } a}{\text{Circumference of } e} \times \frac{\text{number of cogs in } d}{\text{number of cogs in } c} \times \frac{\text{number of cogs in } f}{\text{number of cogs in } b}. \qquad (8)$$

141. The worm wheel. Another device of high mechanical advantage is the worm wheel (Fig. 133). Show that if l is the length of the crank arm C, n the number of teeth in the cogwheel W, and r the radius of the axle, the mechanical advantage is given by

$$\frac{R}{E} = \frac{2\pi l n}{2\pi r} = n\frac{l}{r}. \qquad (9)$$

This device is used most frequently when the primary object is to decrease speed rather than to multiply force. It will be seen that the crank handle must make n turns while the cogwheel is making one. The worm-gear "drive" is generally used in the rear axles of motor trucks.

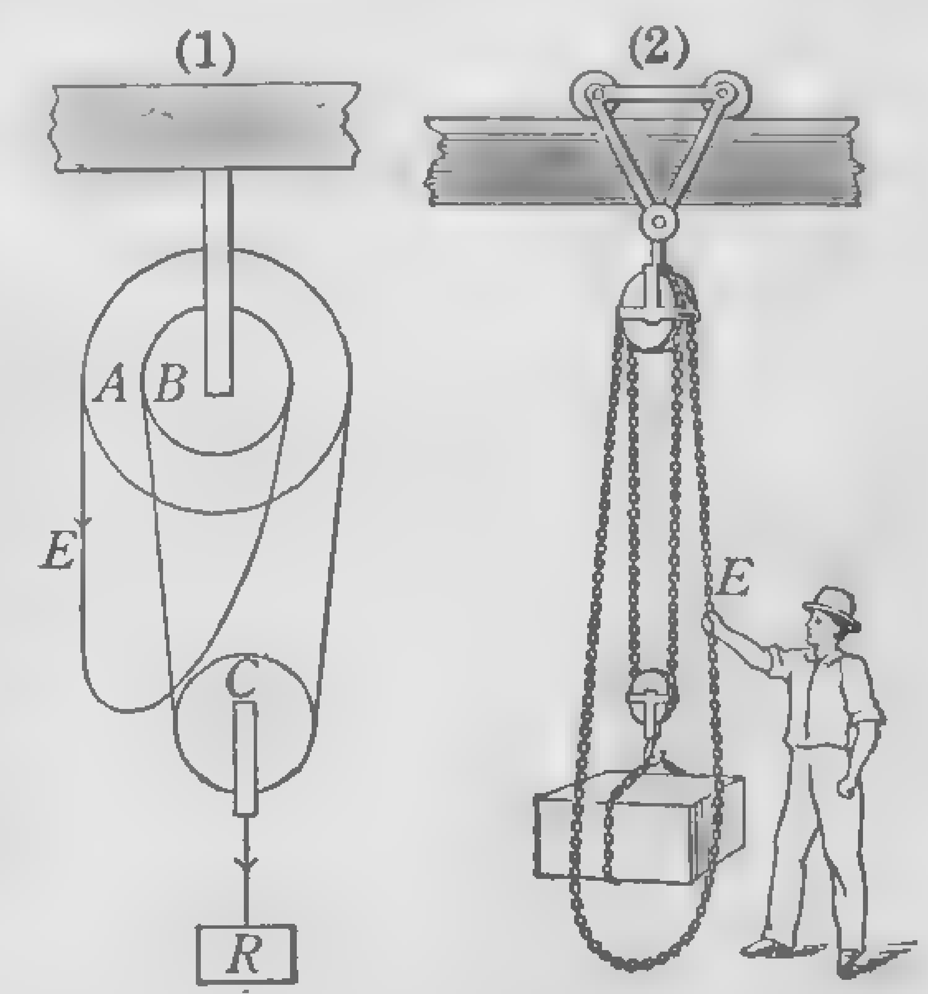


FIG. 134. The differential pulley

142. The differential pulley. In the differential pulley (Fig. 134) an endless chain passes first over the fixed pulley A, then down and around the movable pulley C, then up again over the fixed pulley B, which is rigidly attached to A but differs slightly from it in diameter. On the circumference of all

the pulleys are projections which fit between the links and thus keep the chains from slipping. When the chain is pulled down at E, as in Fig. 134 (2) until the upper rigid system of pulleys has made one complete revolution, the chain between the upper and lower pulleys has been shortened by the difference between the circumferences of the pulleys A and B, for the chain has been pulled up a distance equal to the circumference of the larger pulley and let down a distance equal to the circumference of the smaller pulley. Hence the load R has been lifted by half the difference between the circumferences of A and B. The mechanical advantage is therefore equal to the circumference of A divided by half the difference between the circumferences of A and B.

SUMMARY. *Newton's principle of work.* **In all mechanical devices of whatever sort, if only friction may be neglected, the work expended upon the machine is equal to the work accomplished by it.**

QUESTIONS AND PROBLEMS

1. Name two or three household appliances whose mechanical advantage is less than 1.

2. Analyze several types of manual labor (such, for instance, as messenger service, digging in hard soil and soft soil, chopping or sawing wood, running a lawn mower, gathering in a farm crop, etc.) and see if the definition ($W = Fs$) holds for each. Is not $F \times s$ the thing *paid for* in every case?

3. A force of 80 kg. on a wheel whose diameter is 3 m. balances a weight of 150 kg. on the axle. Find the diameter of the axle.

4. A 1500-pound safe must be raised 5 ft. The force which can be applied is 250 lb. What is the shortest inclined plane which can be used for the purpose?

5. A 300-pound barrel was rolled up a plank 12 ft. long into a doorway 3 ft. high. What force was applied parallel to the plank?

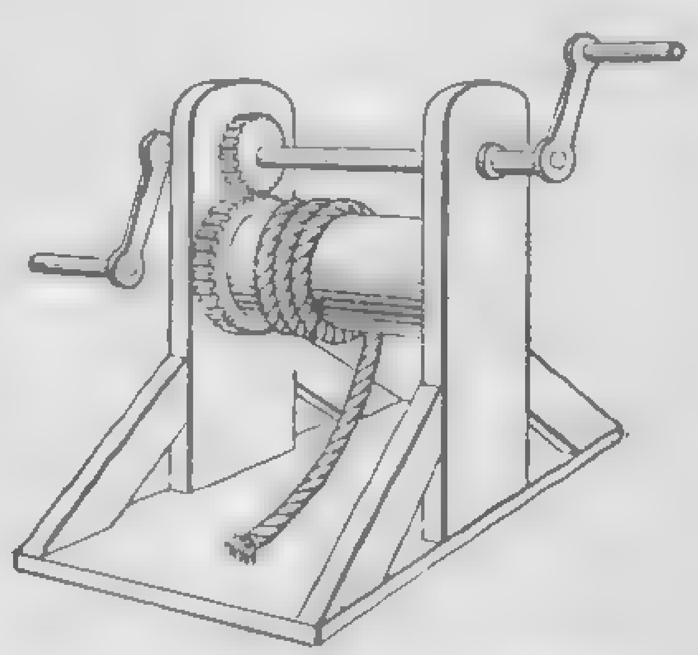


FIG. 135. Windlass with gears

6. In the windlass of Fig. 135 the crank handle has a length of 2 ft., and the barrel a diameter of 8 in. There are 20 cogs in the small cogwheel and 60 in the large one. What is the mechanical advantage of the arrangement?

7. A small jackscrew has 20 threads to the inch. Using a lever $3\frac{1}{2}$ in. long will give what mechanical advantage? (Use 3.1416.)

8. The screw of a lard press has 5 threads to the inch, and the length of each handle is 6 in. If there were no friction, what pressure would result from a rotating force of 10 lb. applied to the end of each handle? (See Fig. 130.)

POWER AND ENERGY

143. Definition of power. Let us suppose that a boy and a man were each sent to load a cart with sand. Although the boy may have been three times as many minutes in loading his cart as was the man, the boy nevertheless performed the same amount of work as did the man, for in loading his cart he raised an equal weight of sand the same height. Time, therefore, is not a factor which enters into the determination of work. In a minute, however, the man accomplished three times as much work as the boy. We say, therefore, that the man worked at three times the *rate* of the boy. *The rate of doing work is called power, or activity.* Thus, if P represents power, W the work done, and t the time required to do the work, then

$$P = \frac{W}{t}, \text{ or } P = \frac{Fs}{t}. \qquad (10)$$

144. Horse power. James Watt (1736–1819), the inventor of the steam engine, considered that an average horse could do 33,000 foot pounds of work per minute, or 550 foot pounds per second. The metric equivalent is 76.05 kilogram meters per second. This number is probably considerably too high; but it has been taken ever since, in English-speaking countries, as the unit of power, and named the *horse power* (H.P.). The power of steam engines has usually been rated in horse power. The horse power of an ordinary railroad locomotive is from 500 to 1000. Stationary engines and steamboat engines of the largest size often run from 5000 to 20,000 H.P.

The power of an average horse is about $\frac{3}{4}$ H.P. and that of an ordinary man about $\frac{1}{7}$ H.P.

145. The kilowatt. In the metric system the erg is taken as the absolute unit of work. The corresponding unit of power is an erg per second. This is, however, so small that it is customary to take as the practical unit 10,000,000 ergs per second; that is, one joule per second (see § 126, p. 115). This unit is called the *watt*, in honor of James Watt. The power of dynamos and electric motors is almost always expressed in kilowatts, a kilowatt representing 1000 watts; and in modern practice even steam engines are being increasingly rated in kilowatts rather than in horse power. A horse power is equivalent to 746 watts, or about $\frac{3}{4}$ of a kilowatt.

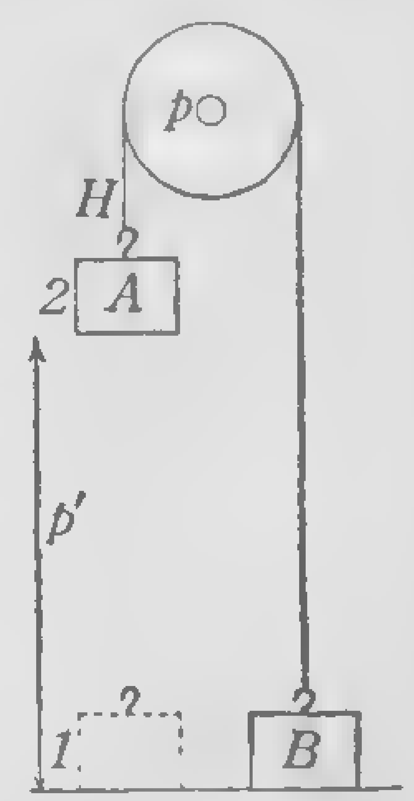


FIG. 136. Illustration of potential energy

146. Definition of energy. The *energy* of a body is defined as its *capacity for doing work*. In general, inanimate bodies possess energy only because of work which has been done upon them at some previous time. Thus, suppose a kilogram weight is lifted from the first position in Fig. 136 through a height of 1 meter and placed upon the hook H at the end of a cord which passes over a frictionless pulley p and is attached at the other end to a second kilogram weight B. The operation of lifting A from position *1* to position *2* has required an expenditure upon it of *1* kilogram meter (100,000 gram centimeters, or 98,000,000 ergs) of work. But in position *2* the weight A is itself possessed of a certain capacity for doing work that it did not have before; for if it is now started downward by the application of the slightest conceivable force, it will of its own accord return to position 1, and will in so doing raise the kilogram weight B through a height of 1 meter. In other words, it will do upon B exactly the same amount of work that was originally done upon it.

THE *ROCKET* AND THE *VIRGINIAN MALLET*

This picture shows the relative sizes of Stephenson's original locomotive, the *Rocket*, which ran in October, 1829, between Manchester and Liverpool, and the largest locomotive thus far built, the *Virginian Mallet*, constructed in the shops of the American Locomotive Company at Schenectady, New York, for use on the Virginian Railroad. The *Rocket* weighed $4\frac{1}{4}$ tons and won a £500 prize by drawing a coach containing 30 people at a rate of from 26 to 30 miles per hour. The *Virginian Mallet* weighs 450 tons and has a tractive power of 176,600 pounds. It has approximately 5100 H.P.

JAMES WATT (1736–1819)

The Scotch instrument maker at the University of Glasgow who may properly be considered the inventor of the steam engine, for although a crude and inefficient type of steam engine was known before his time, he left it in essentially its present form. The modern industrial era may be said to begin with Watt

147. Potential and kinetic energy. A body may have a capacity for doing work not only because it has been given an elevated position but also because it has in some way acquired velocity; for example, a heavy flywheel will keep machinery running for some time after the power has been shut off, and a bullet shot upward will lift itself a great distance against gravity because of the velocity which has been imparted to it. Similarly, any body which is in motion is able to rise against gravity, or to set other bodies in motion by colliding with them, or to overcome resistances of any conceivable sort. Hence, in order to distinguish between the energy that a body may have because of an *advantageous position*, and the energy that it may have because it is in *motion*, the two terms "potential energy" and "kinetic energy" are used. Potential energy includes the energy of lifted weights, of coiled or stretched springs, of bent bows, etc.; in a word, *potential energy is energy of position, and kinetic energy is energy of motion.*

148. Transformations of potential and kinetic energy. The swinging of a pendulum and the oscillation of a weight attached to a spring illustrate very well the way in which energy that has once been put into a body may be transformed back and forth between the potential and kinetic varieties. When the pendulum bob is at rest at the bottom of its arc it possesses no energy of either type, since, on the one hand, it is as low as it can be, and, on the other, it has no velocity. When we pull it up the arc to the position A (Fig. 137) we do upon it an amount of work equal in gram centimeters to its weight in grams times the distance AD in centimeters; that is, we store up in it this amount of potential energy. As now

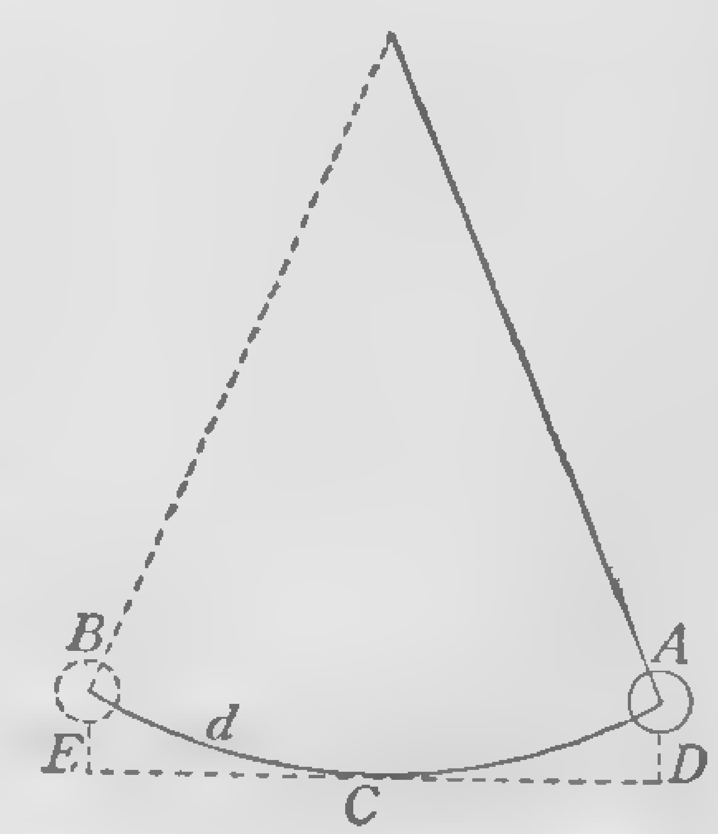


FIG. 137. Transformation of potential and kinetic energy

the bob falls to C this potential energy is completely transformed into kinetic energy. That this kinetic energy at C is exactly equal to the potential energy at A is proved by the fact that if friction is completely eliminated, the bob rises to a point B such that BE is equal to AD. We see, therefore, that at the ends of its swing the energy of the pendulum is all potential, whereas in the middle of the swing its energy is all kinetic. In intermediate positions the energy is part potential and part kinetic, but *the sum of the two is equal to the original potential energy.*

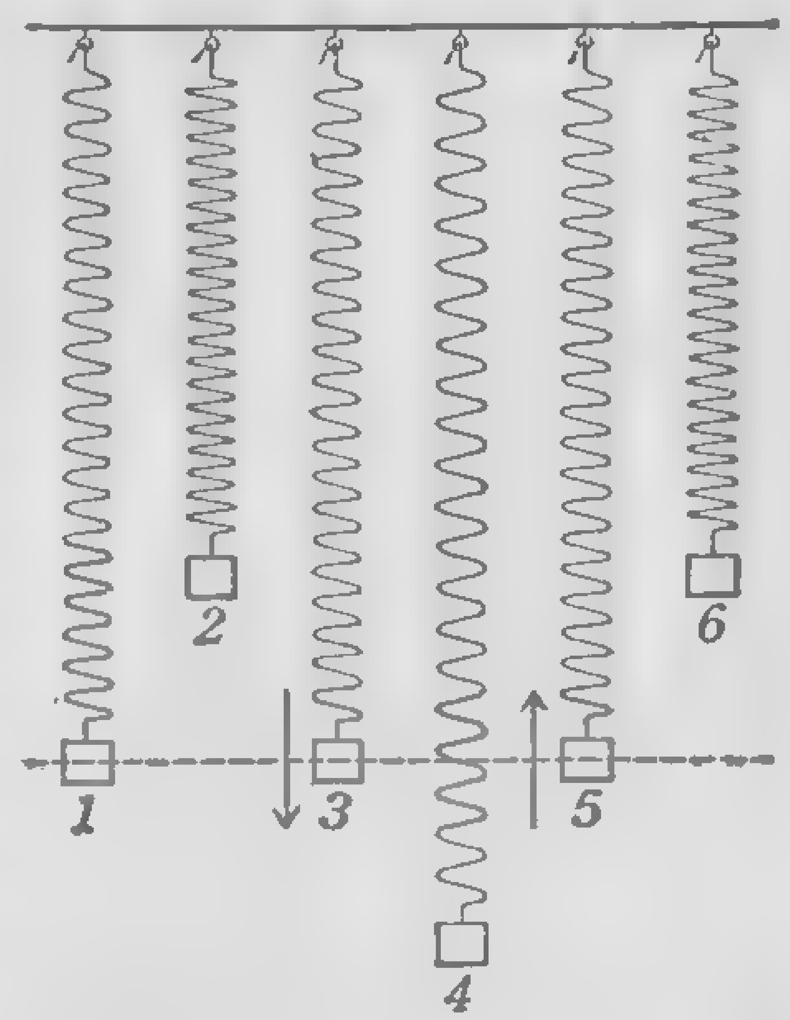


FIG. 138. Transformation of potential and kinetic energy

If a small weight is attached to a long, delicate spiral spring (Fig. 138), and energy is expended to lift the weight from position *1* to position *2*, potential energy is conferred upon it. On suddenly removing the hand the weight slowly falls, and at *3* the energy is all in the kinetic form. As the weight passes to *4* its kinetic energy is transformed into potential energy in the stretched spring, which then lifts the weight to *5*, where the energy is again all in the kinetic form. The kinetic energy in the weight at *5* does the work of lifting it to *6*, where the energy is once more all potential as at *2*.

Opposite page 92 is shown a pile driver, used for pounding big timber into the earth. An engine lifts a very heavy weight to various heights, from which it descends as a freely falling body to do its work. It is kept in a straight course by guides.

149. General statement of the law of frictionless machines. In our development of the law of machines, which led us to the conclusion that the work of the acting force is always equal to the work of the resisting force, we were careful to

make two important assumptions: first, that friction was negligible; secondly, that the motions were all either uniform or so slow that no appreciable velocities were imparted. In other words, we assumed that the work of the acting force was expended simply in lifting weights or in compressing springs; that is, in storing up potential energy. If we drop the second assumption, a very simple experiment will serve to show that our conclusion must be somewhat modified. Suppose, for instance, that instead of lifting a 500-gram weight slowly by means of a balance, we jerk it up suddenly. We shall now find that the initial pull indicated by the balance, instead of being 500 grams, will be considerably more — perhaps as much as several thousand grams if the pull is sufficiently sudden. This is obviously because the acting force is now overcoming not merely the 500 grams which represents the resistance of gravity, but also the inertia of the body, since velocity is being imparted to it. Now work done in imparting velocity to a body (that is, in overcoming its inertia) always appears as *kinetic* energy; work done in overcoming gravity appears as the *potential* energy of a lifted weight. Hence, whether the motions produced by machines are slow or fast, if friction is negligible the law for all devices for transforming work may be stated thus: *The work of the acting force is equal to the sum of the potential and kinetic energies stored up in the mass acted upon.* In machines which work against gravity the body usually starts from rest and is left at rest, so that the kinetic energy resulting from the whole operation is zero. Hence in such cases the work done is the weight lifted times the height through which it is lifted, whether the motion is slow or fast. The kinetic energy imparted to the body in starting is all given up by it in stopping.

150. The measure of potential energy. The measure of the potential energy of any lifted body, such as a lifted pile driver, is equal to the work which has been spent in lifting the body. Thus, if h is the height in centimeters and W the

weight in grams, then the potential energy (P.E.) of the lifted mass is

$$\text{P.E.} = Wh \text{ gram centimeters.} \quad (11)$$

Similarly, if h is the height in feet and W the weight in pounds,

$$\text{P.E.} = Wh \text{ foot pounds.}$$

151. The measure of kinetic energy. Since the force of the earth's attraction for M grams is Mg dynes, if we wish to express the potential energy in ergs instead of in gram centimeters, we have

$$\text{P.E.} = Mgh \text{ ergs.} \quad (12)$$

Since this energy is all transformed into kinetic energy when the mass falls the distance h, the product Mgh also represents the number of ergs of kinetic energy which the moving weight has when it strikes the pile.

If we wish to express this kinetic energy in terms of the velocity with which the weight strikes the pile, instead of the height from which it has fallen, we have only to substitute for h its value in terms of g and the velocity acquired (see equation (7), p. 86); namely, $h = v^2/2g$. This gives the kinetic energy (K.E.) in the form

$$\text{K.E.} = \tfrac{1}{2} Mv^2 \text{ ergs.} \quad (13)$$

Since it makes no difference how a body has acquired its velocity, this represents the general formula for the kinetic energy *in ergs* of any moving body, in terms of its mass and its velocity.

Thus, the kinetic energy of a 100-gram bullet moving with a velocity of 10,000 cm. per second is

$$\text{K.E.} = \tfrac{1}{2} \times 100 \times (10{,}000)^2 = 5{,}000{,}000{,}000 \text{ ergs.}$$

Since 1 g. cm. is equivalent to 980 ergs, the energy of this bullet is $5{,}000{,}000{,}000/980 = 5{,}102{,}000$ g. cm., or 51.02 kg. m.

We know, therefore, that the powder pushing on the bullet as it moved through the rifle barrel did 51.02 kg. m. of work upon the bullet in giving it the velocity of 100 m. per second.

In general terms, if M is in grams and v in centimeters per second, $\text{K.E.} = \frac{1}{2}Mv^2/980$ g. cm.; if M is in pounds and v in feet per second, $\text{K.E.} = \frac{1}{2}Mv^2/32.16$ ft. lb.

Summary. **Power, or activity, is the rate of doing work; that is, $P = W/t$.**

One horse power = 33,000 foot pounds per minute = 550 foot pounds per second = 746 watts = $\frac{3}{4}$ kilowatt.

One watt = 10,000,000 ergs per second = 1 joule per second.

The energy of a body is its capacity for doing work. Kinetic energy is energy of motion; potential energy is energy of position.

General law of ideal frictionless machines when velocity is being imparted to mass. **The work of the acting force is equal to the sum of the potential and kinetic energies stored up in the mass acted upon.**

The potential energy of an uplifted weight equals its weight times its height; that is, P.E. = Wh gravitational units = Mgh absolute units.

The kinetic energy of a moving mass equals $Mv^2/2$ absolute units, or $Mv^2/2g$ gravitational units.

QUESTIONS AND PROBLEMS

1. An electric motor hoisted a block of granite weighing 6600 lb. 100 ft. in 2 min. At what power (expressed as foot pounds per minute) was work done on the block of granite? What is this rate expressed as horse power?

2. What horse power is needed to draw a load of 5 t. at a uniform rate up a hill 50 ft. high in 10 min.?

3. What horse power is required to run an automobile on a level road at the rate of 30 mi. per hour if the forces of friction amount to 125 lb.?

4. A farm tractor drew a gang plow at the rate of $2\frac{1}{2}$ mi. per hour, maintaining an average drawbar pull of 1500 lb. At what average horse power was the tractor working?

5. A stick of dynamite has great capacity for doing work. Before the explosion occurs, is the energy in the potential form or in the kinetic form?

6. Explain the use of the sand blast in cleaning castings, making frosted glass, cutting figures on glassware, cleaning off the walls of stone buildings, etc.

7. How much work is required to lift the 500-pound weight of a pile driver 30 ft.? How much potential energy is then stored in it? How much work does it do when it falls? If the falling mass drives the pile into the earth $\frac{1}{2}$ ft., what is its average force upon the pile? (See opposite page 92.)

8. In the course of a stream there is a waterfall 22 ft. high. It is shown by measurement that 450 cu. ft. of water per second

pours over it. What power in foot pounds of energy per second could be obtained from it? What horse power?

9. If a rifle weighing 5 kg. fired a bullet weighing 10 g. with a velocity of 700 m. per second, what was the velocity of recoil of the rifle? (Use Newton's third law.)

10. Show that the energy of the bullet exceeds that of the rifle.

Friction

152. Friction always results in wasted work. All the experiments mentioned in this chapter have been so arranged that *friction* could be neglected or eliminated. So long as this condition was fulfilled it was found that the result of universal experience could be stated thus: *The work done by the acting force is equal to the sum of the kinetic and potential energies stored up* (§ 149).

But wherever friction is present this law is found to be inexact, for the work of the acting force is then always somewhat greater than the sum of the kinetic and potential energies stored up. If, for example, a block is pulled over the horizontal surface of a table, at the end of the motion no velocity has been imparted to the block, and hence no kinetic energy has been stored up. Furthermore, the block has not been lifted nor put into a condition of elastic strain, and hence no potential energy has been communicated to it. We cannot in any way obtain from the block more work after the motion than we could have obtained before it was moved. It is clear, therefore, that all the work which was done in moving the block against the friction of the table was *wasted work*. Experience shows that, in general, where work is done against friction it can never be regained. Before considering what becomes of this wasted work we shall consider some of the factors on which friction depends and some of the laws that are found by experiment to hold in cases in which friction occurs.

153. The coefficient of friction. It is found that if F represents the force parallel to a plane which is necessary to

maintain uniform motion in a body that is pressed against the plane with a force F', then, *for small velocities*, the ratio F/F' depends only on the nature of the surfaces in contact and not at all on the area or on the velocity of the motion. The ratio F/F' is called the *coefficient of friction* for the given materials. Thus (Fig. 139), if F is 300 grams and F' is 800 grams, the coefficient of friction is $\frac{300}{800} = .375$. The coefficient of iron on iron is about .2; of oak on oak, about .4.

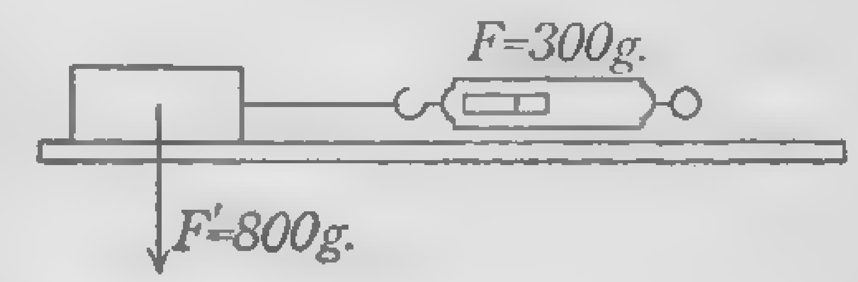


FIG. 139. The ratio of F to F' is the coefficient of friction

154. Rolling friction. The chief cause of sliding friction is the interlocking of minute projections. When a round solid *rolls* over a smooth surface, the frictional resistance is generally much less than when it slides; for example, the coefficient of friction of cast-iron wheels rolling on iron rails may be as low as .002; that is, $\frac{1}{100}$ of sliding friction of iron on iron. This means that a pull of 1 lb. will keep a 500-pound car in motion. Sliding friction is not, however, entirely dispensed with in ordinary wheels; for although

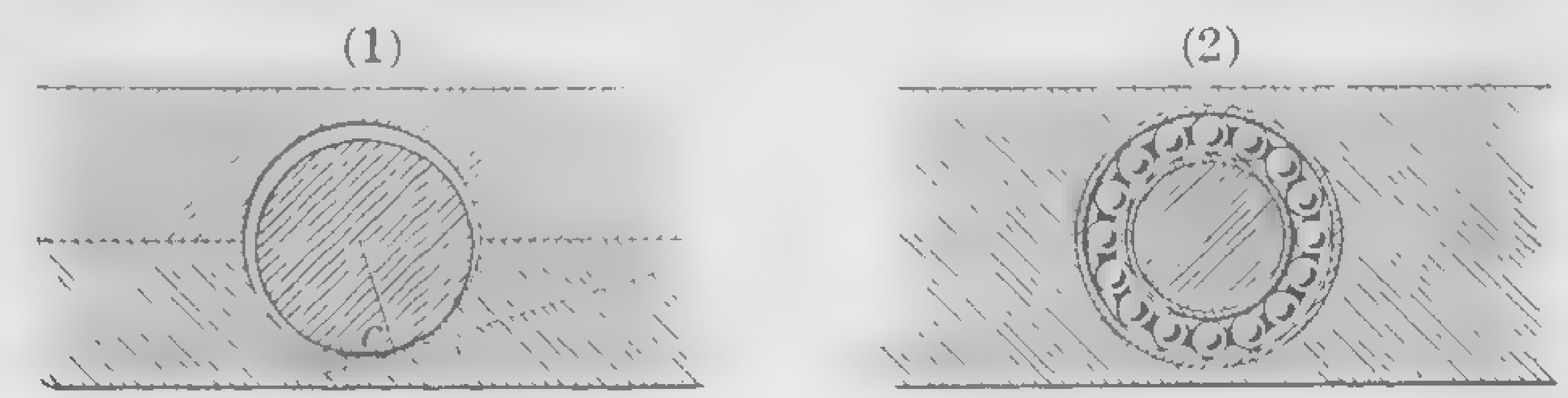


FIG. 140. Friction in bearings: (1) common bearing; (2) ball bearing

the rim of the wheel rolls on the track, the axle slides continuously at some point c (Fig. 140 (1)) upon the surface of the journal. Journals are frequently lined with brass or Babbitt metal, since this lowers the coefficient still further.

The great advantage of ball bearings (Fig. 140 (2)) is that the sliding friction in the hub is almost completely replaced by rolling friction. The manner in which ball bearings are used in a bicycle pedal is illustrated in Fig. 141. The free-wheel ratchet is shown in Fig. 142. The pawls a and b enable the pedals and the chain wheel W to stop while the rear axle continues to revolve. Roller bearings

are shown in Fig. 143, in which the white areas represent the extremely hard steel cones upon which the rollers bear. Oils, greases, graphite, and other lubricants prevent rapid wear of bearings by lessening friction.

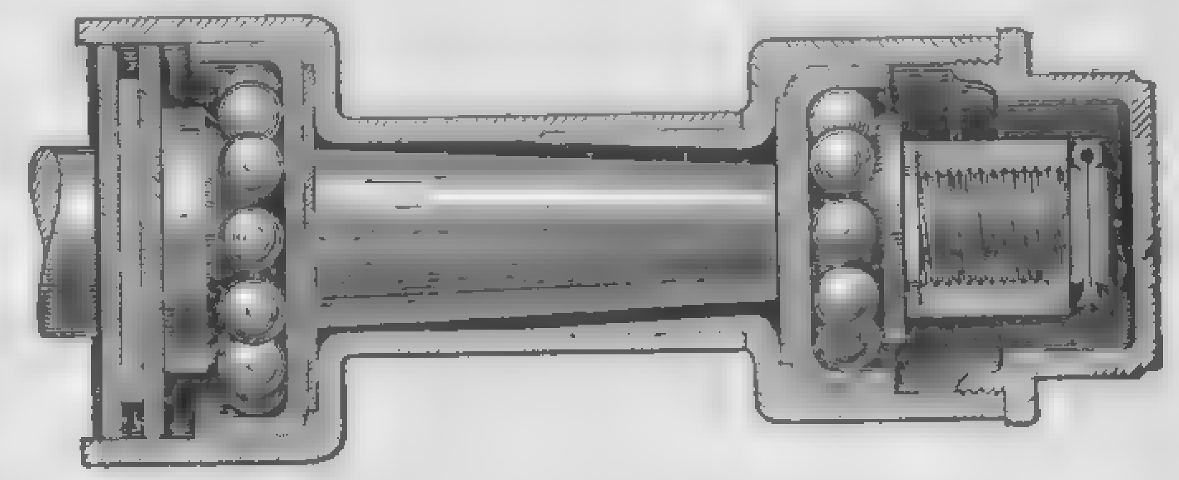


FIG. 141. The bicycle pedal

155. Friction of fluids. When a solid moves through a fluid, as when a bullet moves through the air or a ship moves through the water, the resistance encountered is not at all independent of velocity, as in the case of solid friction, but increases for slow speeds nearly as the square of the velocity and for high speeds at a rate considerably greater. This explains why it is so expensive to run a fast train; for the resistance of the air, which is a small part of the total resistance so long as the train is moving slowly, becomes the predominant factor at high speeds. The resistance offered to steamboats running at high speeds is usually considered to increase as the cube of the velocity. Thus, the *Cedric*, of the White Star Line, having a speed of 17 knots, has a horse power of 14,000 and a total weight when loaded of about 38,000 tons; whereas the *Mauretania*, of the Cunard Line, having a speed of 25 knots, has engines of 70,000 horse power, although the total weight when loaded is only 32,500 tons.

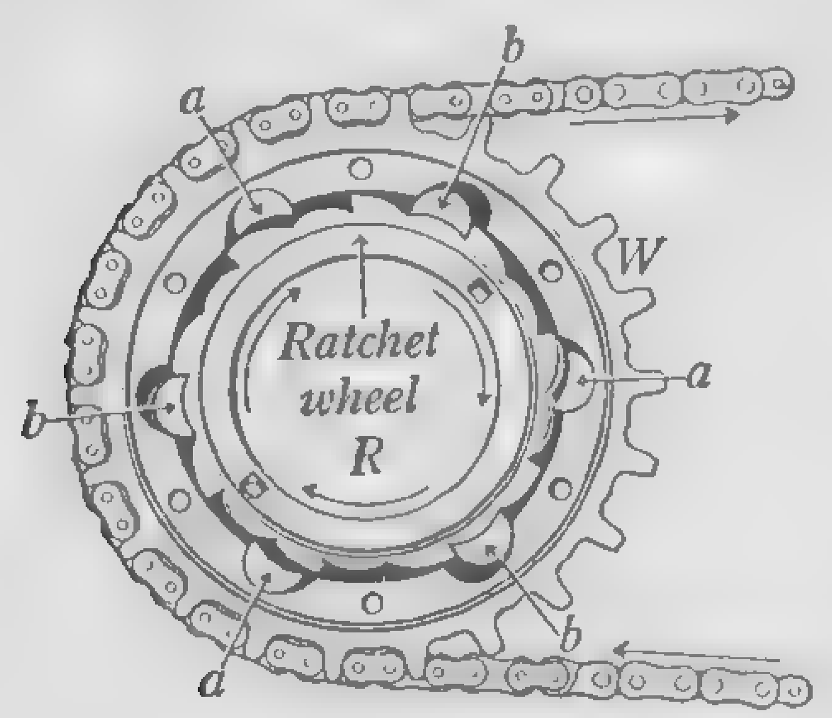


FIG. 142. Free-wheel ratchet

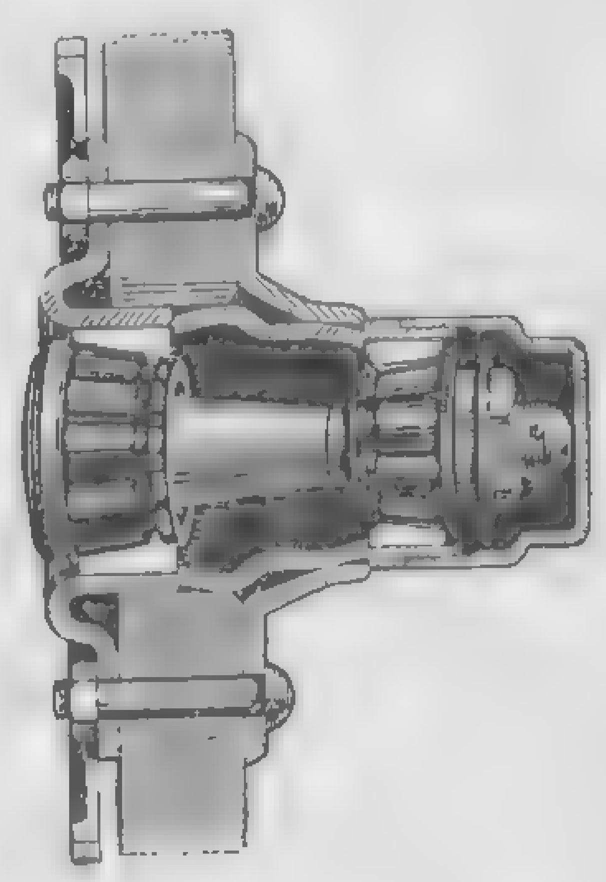


FIG. 143. Roller bearings of automobile front wheel

SUMMARY. **Work done against friction is entirely wasted. The coefficient of friction is the ratio of the tangential force required to overcome friction to the normal force pressing the surfaces together.**

QUESTIONS AND PROBLEMS

1. Why is sand often placed on a track in starting a heavy train?

2. In what way is friction an advantage in lifting buildings with a jackscrew? In what way is it a disadvantage?

3. Why is a stream swifter at the center than at the banks?

4. Why does a team have to keep pulling after a load is started?

5. In what respects is friction an advantage in everyday life? In what respects is it a disadvantage? Could we get along without it?

6. Mention three ways of lessening friction in machinery.

7. What is the coefficient of friction of brass on brass if a force of 25 lb. is required to maintain uniform motion in a brass block weighing 200 lb. when it slides horizontally on a brass bed?

8. The coefficient of friction between a block and a table is .3. What force will be required to keep a 500-gram block in uniform motion?

9. What horse power must be used to pull a body weighing 5 t. along a horizontal surface at the rate of 6 mi. per hour, the coefficient of friction being .2?

EFFICIENCY

156. Definition of efficiency. Since it is only in an ideal machine that there is no friction, in all actual machines the work done by the acting force always exceeds, by the amount of the work done against friction, the amount of potential and kinetic energy stored up. We have seen that the former is wasted work in the sense that it can never be regained. Since the energy stored up represents work which can be regained, it is termed *useful work.* In most machines an effort is made to have the useful work as large a fraction of the total work expended as possible. *The ratio of the useful*

work to the total work done by the acting force is called the EFFICIENCY *of the machine.* Thus,

$$\text{Efficiency} = \frac{\text{useful work accomplished}}{\text{total work expended}}, \text{ or } \frac{\text{output}}{\text{input}}. \quad (14)$$

Thus, if in the system of pulleys shown in Fig. 114 it is necessary to add a weight of 50 g. at E in order to pull up slowly an added weight of 240 g. at R, the work done by the 50 g. while E is moving over 1 cm. will be 50×1 g. cm. The useful work accomplished in the same time is $240 \times 1/6$ g. cm. Hence the efficiency is equal to

$$\frac{240 \times \frac{1}{6}}{50 \times 1} = \frac{4}{5} = 80 \text{ per cent.}$$

157. Efficiencies of some simple machines. In simple levers the friction is generally so small as to be negligible; hence the efficiency of such machines is approximately 100 per cent. When inclined planes are used as machines the friction is also small, so that the efficiency generally lies between 90 per cent and 100 per cent. The efficiency of the commercial block and tackle (Fig. 114), with several movable pulleys, is usually considerably less, varying between 40 per cent and 60 per cent. In the jackscrew there is necessarily a very large amount of friction, so that although the mechanical advantage is enormous, the efficiency is often as low as 25 per cent. The differential pulley of Fig. 134 has also a very high mechanical advantage with a very small efficiency. Gear wheels such as those shown in Fig. 132, or chain gears such as those used in bicycles, are machines of comparatively high efficiency, often utilizing between 90 per cent and 100 per cent of the energy expended upon them.

158. Efficiency of overshot water wheels. The overshot water wheel (Fig. 144) utilizes chiefly the potential energy of the water at S, for the wheel is turned by the weight of the water in the buckets. The work expended on the wheel per second, in foot pounds or in gram centimeters, is the product of the weight of the water which passes over it per second by the distance through which it falls. The efficiency is the work which the wheel can

accomplish in a second divided by this quantity. Such wheels are very common in mountainous regions, where it is easy to obtain considerable fall but where the streams carry a small *volume* of water. The efficiency is high, being often between 80 per cent and 90 per cent. The loss is due not only to the friction in the bearings and gears (see C) but also to the fact that some of the water is spilled from the buckets or passes over without entering them at all. This may still be regarded as a frictional loss, since the energy disappears in internal friction when the water strikes the ground.

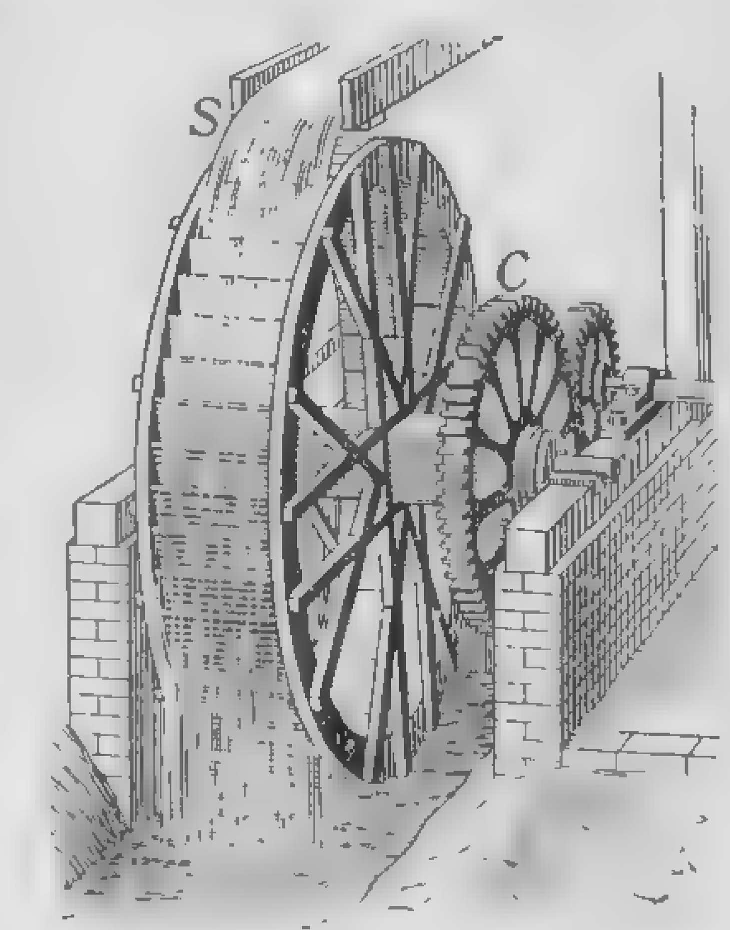


FIG. 144. Overshot water wheel

159. Efficiency of undershot water wheels. The old-style undershot wheel (Fig. 145), so common in flat countries, where there is little fall but an abundance of water, utilizes only the kinetic energy of the water running through the race from A. It seldom transforms into useful work more than 25 per cent or 30 per cent

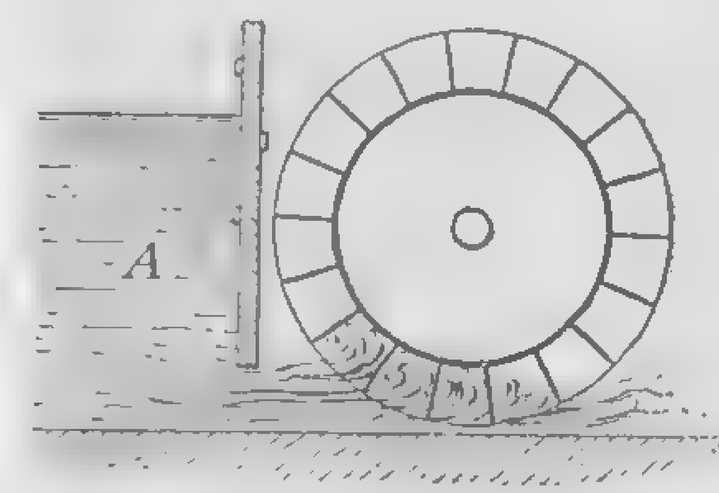


FIG. 145. The undershot wheel

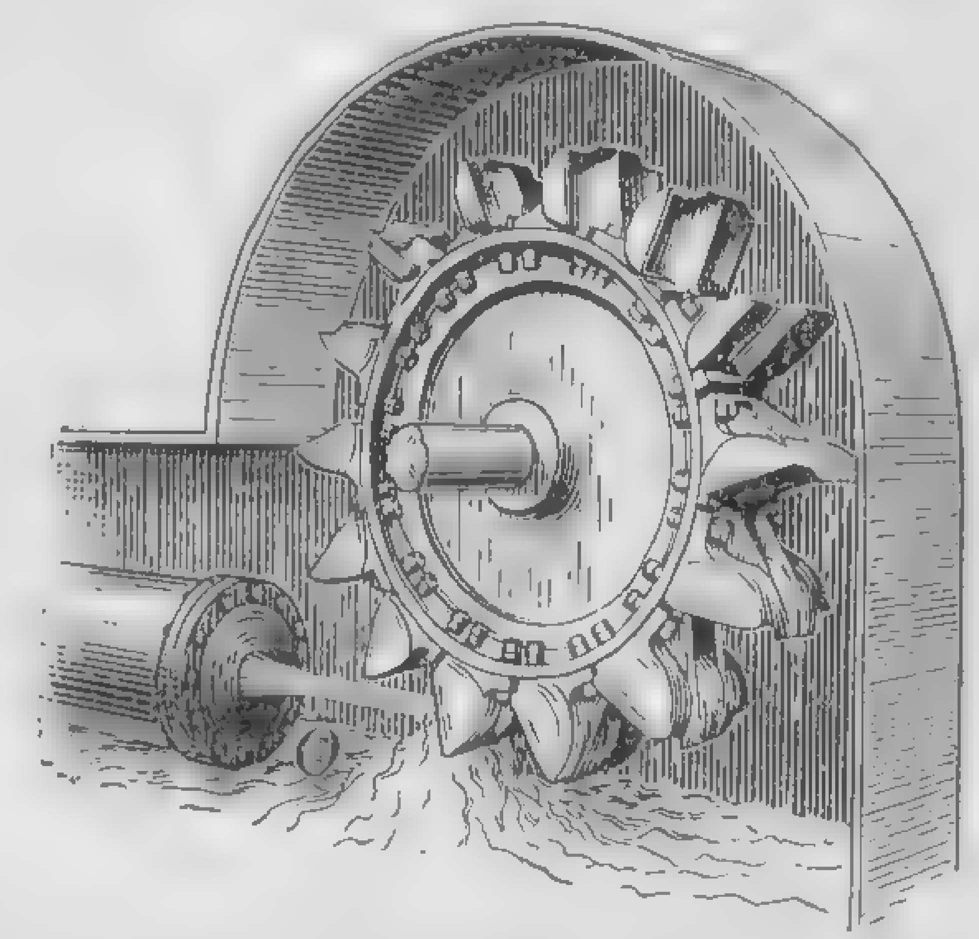


FIG. 146. The Pelton water wheel

of the potential energy of the water above the dam. There are, however, certain modern forms of undershot wheel which are extremely efficient. For example, the *Pelton wheel* (Fig. 146), developed since 1880 and now very commonly used for small-power purposes in cities supplied with waterworks, as well as for operating huge power plants, sometimes has an efficiency as high

as 87 per cent. The water is delivered from a nozzle O against cup-shaped buckets arranged as in the figure. At the Big Creek development in California, Pelton wheels 121 in. in diameter are driven by water coming with a velocity of 350 ft. per second (how many miles per hour?) through nozzles 6 in. in diameter. The head of water (drop) is here 2130 ft. (See opposite page 145.)

160. Efficiency of water turbines. The turbine wheel was invented in France in 1833 and is now used more than any other form of water wheel. It stands completely under water in a case at the bottom of a *turbine pit* and rotates in a horizontal plane. Fig. 147 (1) shows one form of outer case with contained turbine; Fig. 147 (2) is the inner case, in which are the fixed guides G, which direct the water at the most advantageous angle against the blades of the wheel inside; Fig. 147 (3) is the wheel itself; and Fig. 147 (4) is a section of wheel and inner case, showing how the water enters through the guides and impinges upon the blades W. The spent water simply falls down from the blades into the tailrace below T (Fig. 147 (1)). The amount of water which passes through the turbine can be controlled by means of a valve P (Fig. 147 (1)), which can be turned so as to increase or decrease the size of the openings between the guides G (Fig. 147 (2)). On the opposite page is shown a huge modern turbine installation. The energy expended upon the turbine per second is the product of the weight of water which passes through it by the height of the turbine pit. Efficiencies as high as 93 per cent have been attained with such wheels.

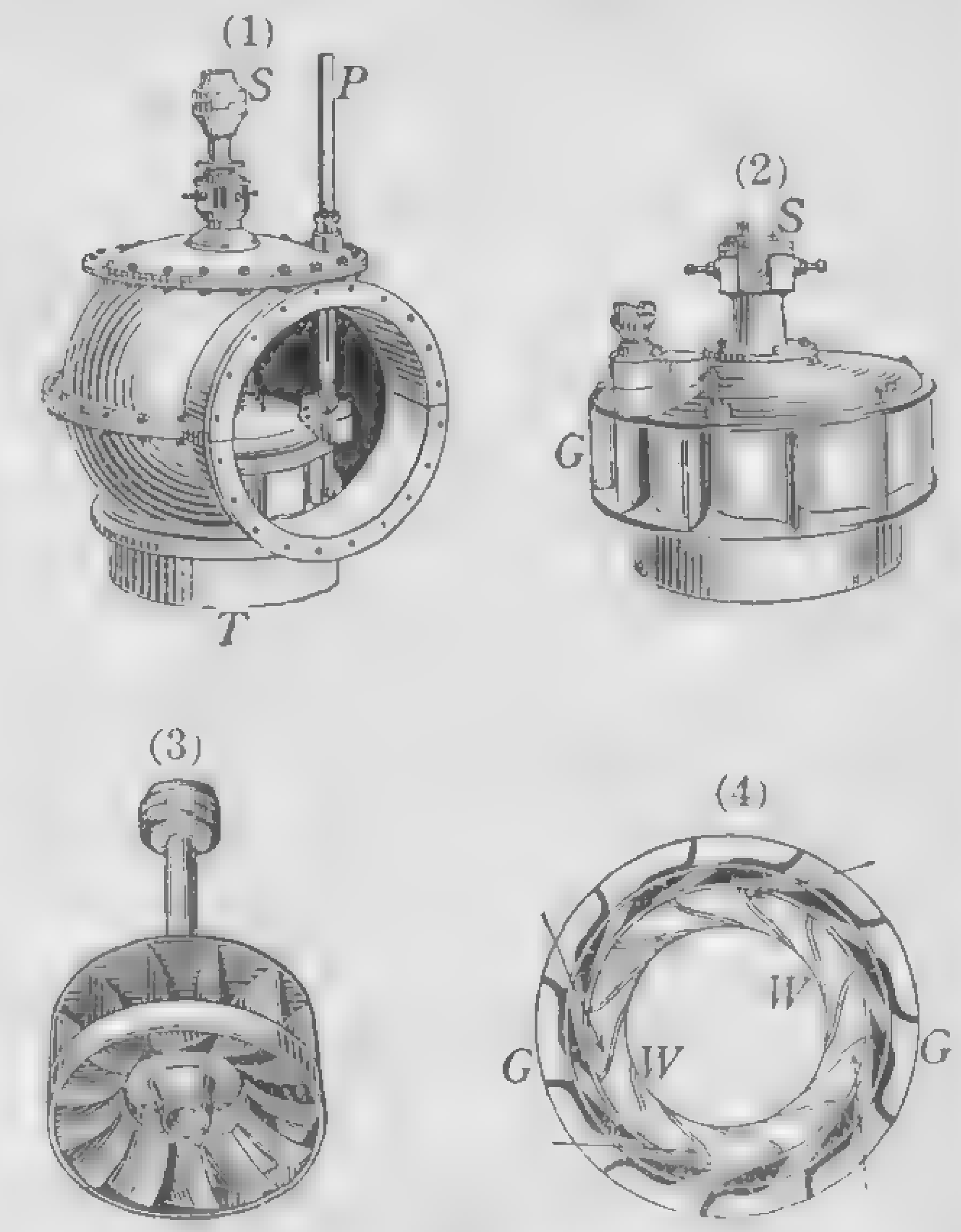
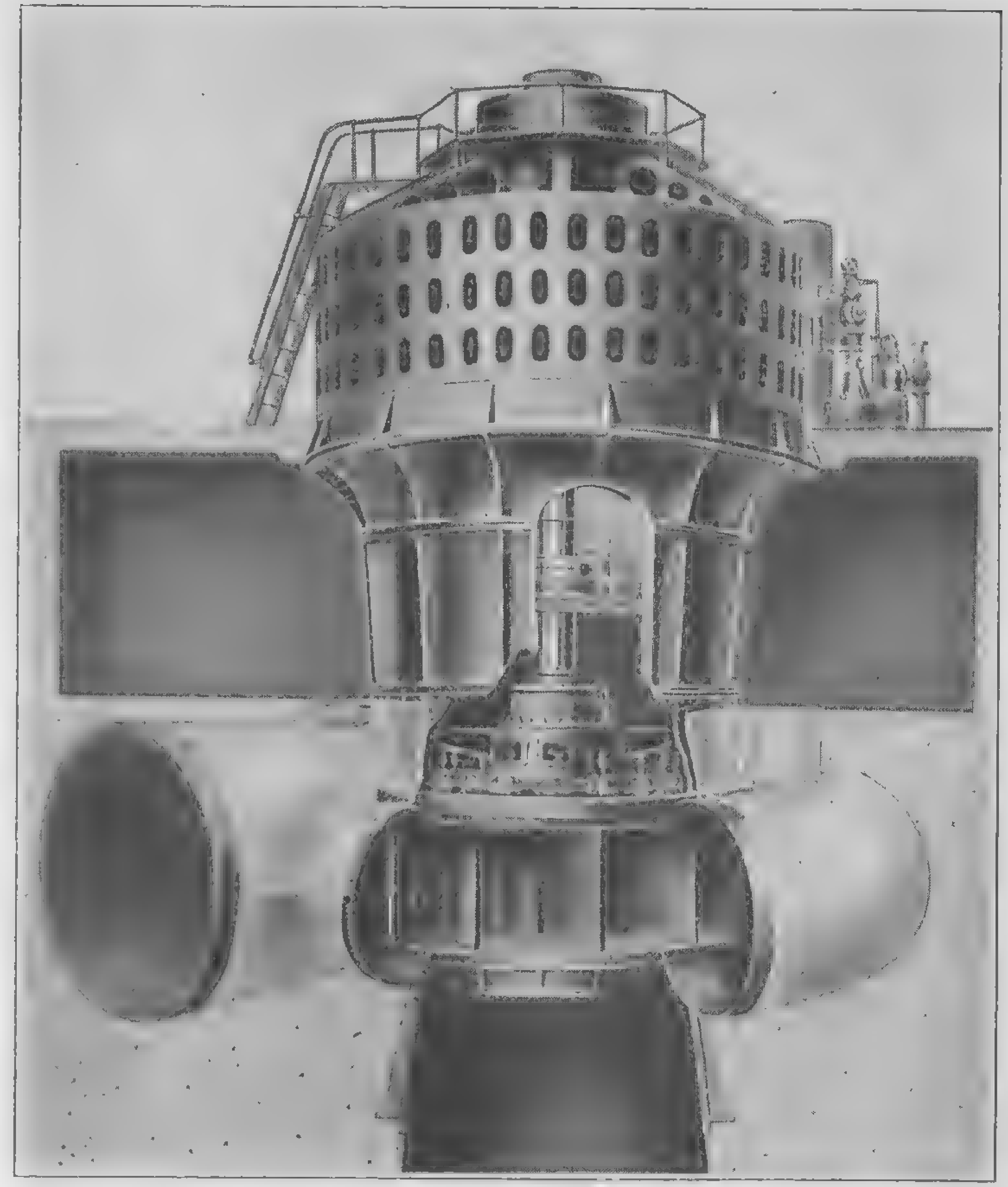


FIG. 147. The turbine wheel: (1) outer case; (2) inner case; (3) rotating part; (4) section



A TURBO-GENERATOR

On the American side of the Niagara River are installed three turbines, similar to the one shown in the picture, of 70,000 H.P., each operating under a head of 213.5 feet. They are the highest-powered turbines in the world. The picture shows clearly how the water enters a volute casing surrounding the whole wheel, from which it is evenly distributed against the blades of the huge runner 15 feet in diameter. Each of these complete turbines, not including the generators above, weighs 1,250,000 pounds, makes 107 R.P.M., and has an efficiency of 93 per cent. The generator shaft is of solid steel 34 inches in diameter. (Courtesy of the Westinghouse Electric and Manufacturing Company)

A HYDROELECTRIC PLANT IN THE HIGH SIERRAS

This is one of the Southern California Edison Company's hydroelectric power plants. Large water storage at an elevation of 7000 feet is obtained by two huge dams and a 13-mile-long tunnel through granite rock. The vertical drop of this water through more than a mile is fully utilized by a series of power plants. The picture shows one of these in which are installed Pelton wheels fed from a penstock 4333 feet long (seen on the mountain side) and having a vertical drop of 2130 feet. Each of these Pelton wheels has a maximum output of 43,000 H.P. and an efficiency of 88 per cent. The power is transmitted 241 miles at 220,000 volts

SUMMARY. The efficiency of a machine is the ratio of its useful output of work to the total input of work (work done on the machine); that is,

$$\textbf{Efficiency} = \frac{\textbf{output}}{\textbf{input}}.$$

The efficiency of the simple machines varies greatly: in the case of a simple lever it may be almost 100 per cent and in the jackscrew as low as 25 per cent.

QUESTIONS AND PROBLEMS*

1. (1) Distinguish between the mechanical advantage of a machine and its efficiency. (2) How is each calculated?

2. Why is the efficiency of the jackscrew low and that of the lever high?

3. Find the efficiency of a machine in which an effort of 12 lb. moving 5 ft. raises a weight of 25 lb. 2 ft.

4. Compute the efficiency of a machine which is run by a 2-horse-power motor if the machine can do but 50,000 ft. lb. of work per minute.

5. A wheel and axle was used to hoist 200 lb. from a well 50 ft. deep. The hands of the workman at the wheel made 100 complete revolutions of 8 ft. circumference each with an average force of 15 lb. Find (1) the efficiency of the machine; (2) the number of foot pounds of energy not utilized.

6. A steam shovel driven by a 5-horse-power engine lifts 200 t. of gravel to a height of 15 ft. in an hour. What is the efficiency of the steam shovel? What percentage of the power is lost because of friction?

7. (1) At what average horse power does a man work who loads 30 bricks a minute from the ground to a wagon 4 ft. from the ground? Each brick weighs 7 lb. (2) What is his efficiency if he tosses them 1 ft. higher than necessary?

8. What amount of work was done on a block and tackle having an efficiency of 60 per cent when by means of it a weight of 750 lb. was raised 50 ft.?

*Supplementary questions and problems for Chapter VII are given in the Appendix.

CHAPTER VIII

THERMOMETRY; EXPANSION COEFFICIENTS*

THERMOMETRY

161. Meaning of temperature. When a body feels hot to the touch we are accustomed to say that it has a *high temperature*; when it feels cold we say that it has a *low temperature.* Thus the word "temperature" is used to denote the condition of hotness or coldness of the body whose state is being described.

162. Measurement of temperature. So far as we know, up to the time of Galileo no one had ever used any special instrument for the measurement of temperature. People knew how hot or how cold it was from their feelings only. But under some conditions this sense of temperature is a very unreliable guide. For example, if the hand has been in hot water, tepid water will feel cold; if it has been in cold water, the same tepid water will feel warm; a room may feel warm to one who has been running, whereas it will feel cool to one who has been sitting still.

Difficulties of this sort have led to the introduction in modern times of mechanical devices called *thermometers*, for measuring temperature. These instruments depend for their operation upon the fact that almost all bodies expand as they grow hot.

163. Galileo's thermometer. It was in 1592 that Galileo, at the University of Padua, constructed the first thermometer. He was familiar with the facts of expansion of solids, liquids, and gases; and since gases expand more than solids or liquids,

* It is recommended that this chapter be preceded by laboratory measurements on the expansions of a gas and a solid. See, for example, Experiments 20 and 21 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

he chose a gas as his expanding substance. His device was that shown in Fig. 148.

Let a bulb of air B be connected with a water manometer m, as in Fig. 148. If the bulb is warmed by holding a Bunsen burner beneath it, or even by placing the hand upon it, the water at m will at once begin to descend, showing that the pressure exerted by the air contained in the bulb has been increased by the increase in its temperature. If B is cooled with ice or ether, the water will rise at m.

FIG. 148. Expansion of air by heat

164. Significance of temperature from the standpoint of the kinetic theory. If, as was stated in § 64, gas pressure is due to the bombardment of the walls by the molecules of the gas, then, since the number of molecules in the bulb can scarcely have been changed by slightly heating it, we are forced to conclude that the increase in pressure is caused by an increase in the *velocity* of the molecules which are already there. From the standpoint of the kinetic theory the pressure exerted by a given number of molecules of a gas is determined by the kinetic energy of bombardment of these molecules against the containing walls. To increase the temperature is to increase the average kinetic energy of the molecules; to diminish the temperature is to diminish this average kinetic energy. The kinetic theory thus furnishes a very simple and natural explanation of the fact of the expansion of gases with a rise in temperature.

165. Construction of a centigrade mercury thermometer. Forty years after Galileo invented his air thermometer, Jean Rey, a Frenchman, made water instead of air the thermometric substance by inverting Galileo's thermometer and filling the bulb and part of the stem with this liquid. Thermometer tubes were not sealed at the top until a quarter of a century later. It was not until about 1700 that mercury thermometers were invented. On account of their much greater convenience these have now replaced all others for practical purposes.

The meaning of a degree of temperature change as measured by a mercury thermometer is best understood from a description of the method of making and graduating the thermometer.

A bulb is blown at one end of a piece of thick-walled glass tubing of small, uniform bore. Bulb and tube are filled with mercury at a temperature slightly above the highest temperature for which the thermometer is to be used, and the tube is sealed off in a hot flame. As the mercury cools it contracts and falls away from the top of the tube, leaving a vacuum above it.

The bulb is next surrounded with melting snow or ice, as in Fig. 149, and the point at which the mercury stands in the tube is marked 0°. Then the bulb and tube are placed in the steam rising from boiling water under a pressure of 76 cm., as in Fig. 150, and the new position of the mercury is marked 100°. The space between these two marks on the stem is then divided into 100 equal parts, and divisions of the same length are extended above the 100° mark and below the 0° mark.

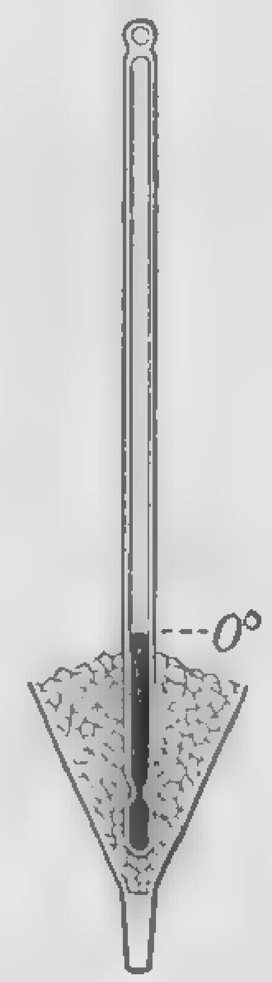


FIG. 149. Method of finding the 0° point in calibrating a thermometer

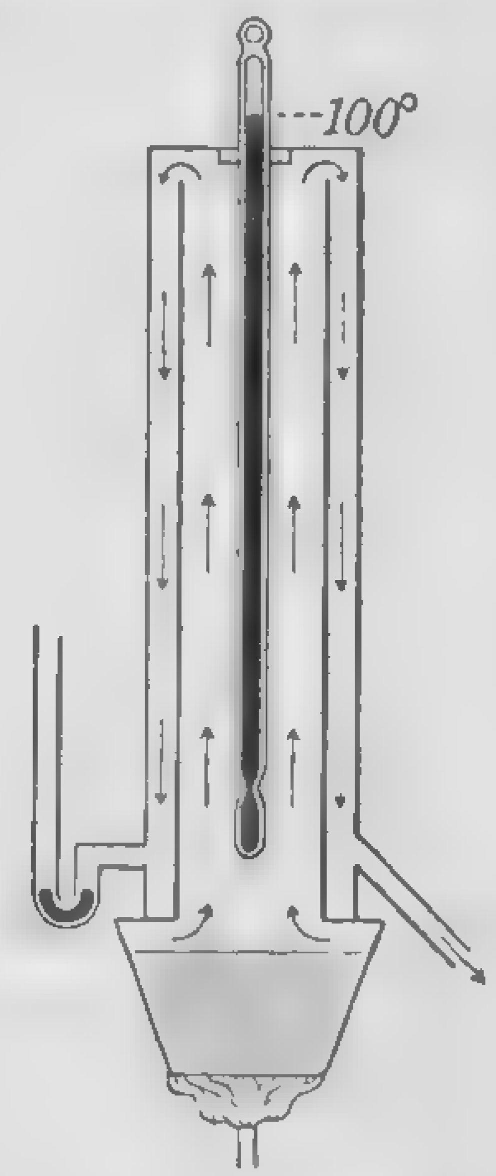


FIG. 150. Method of finding the 100° point in calibrating a thermometer

Therefore *one degree* of change in temperature, measured on such a thermometer, means such a temperature change as will cause the mercury in the stem to move over one of these divisions; that is, it is such a temperature change as will cause mercury contained in a glass bulb to expand $\frac{1}{100}$ of the amount which it expands in passing from the temperature of melting ice to that of steam under a pressure of 76 cm.

A thermometer in which the scale is divided in this way is called a centigrade thermometer.

Thermometers graduated on the centigrade scale are used almost exclusively in scientific work, and also for ordinary purposes in most countries which have adopted the metric system. This scale was first devised in 1742 by Celsius, of Upsala, Sweden. For this reason it is sometimes called the Celsius scale instead of the centigrade.

According to the kinetic theory an increase in temperature in a liquid, as in a gas, means an increase in the mean kinetic energy of the molecules; conversely, a decrease in temperature means a decrease in this average kinetic energy.

166. Fahrenheit thermometers. The common household thermometer in England and the United States differs from the centigrade only in the manner of its graduation. In its construction the temperature of melting ice is marked 32° instead of 0°, and that of boiling water 212° instead of 100°. The intervening stem is then divided into 180 parts. The zero of this scale is the temperature obtained by mixing equal weights of sal ammoniac (ammonium chloride) and snow. In 1714, when Fahrenheit devised this scale, he chose this zero because he thought it represented the lowest possible temperature that could be obtained in the laboratory.

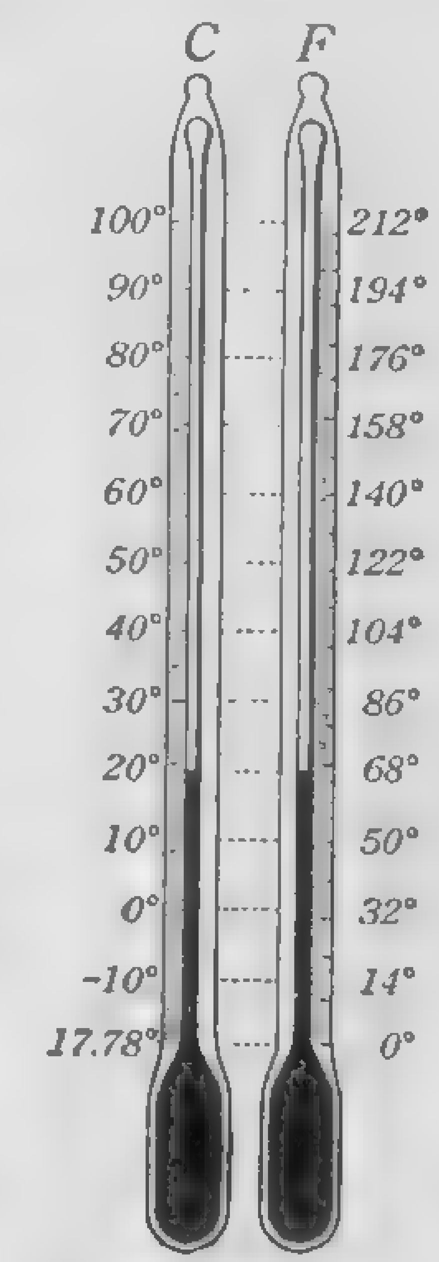


FIG. 151. The centigrade and Fahrenheit scales

167. Comparison of centigrade and Fahrenheit thermometers. From the methods of graduation of the Fahrenheit and centigrade thermometers it will be seen that 100° on the centigrade scale denotes the same difference of temperature as 180° on the Fahrenheit scale (Fig. 151). Hence a temperature difference of five centigrade degrees is equal to nine Fahrenheit degrees. Hence, *to change from C. to F. tem-*

peratures, multiply by $\frac{9}{5}$ and add 32; to change from F. to C. temperatures subtract 32 and multiply by $\frac{5}{9}$.

168. Range of the mercury thermometer. Since mercury freeezes at $-39°$ C., temperatures lower than this are very often measured by means of *alcohol* thermometers, for the freezing point of alcohol is $-130°$ C. Similarly, since the boiling point of mercury is about 357° C., mercury thermometers can not be used for measuring very high temperatures. For both very high and very low temperatures — in fact, for all temperatures — a *gas* thermometer is the standard instrument.

169. The standard hydrogen thermometer. The modern gas thermometer (Fig. 152) is, however, widely different from that devised by Galileo (Fig. 148). It is not usually the increase in the volume of a gas kept under constant pressure which is taken as the measure of temperature change, but rather the increase in pressure which the molecules of a confined gas exert against the walls of a vessel the volume of which is kept constant. The essential features of the method of calibration and use of the standard hydrogen thermometer at the International Bureau of Weights and Measures at Paris are as follows:

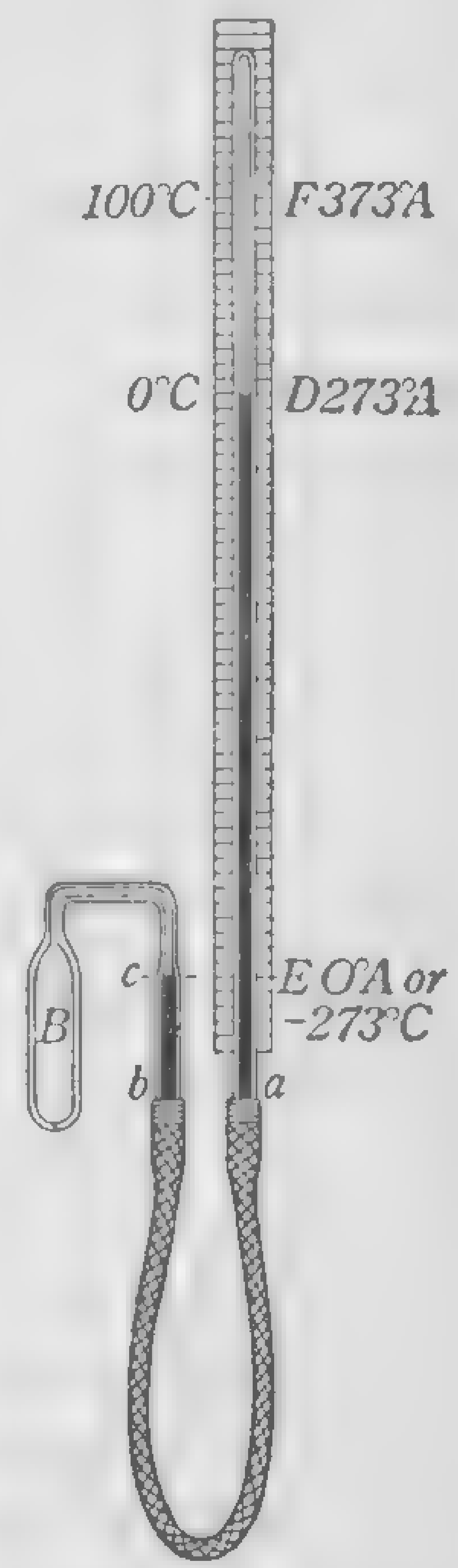


Fig. 152. The standard gas thermometer

First the bulb B (Fig. 152) is filled with hydrogen and the space above the mercury in the tube a is made as nearly a perfect vacuum as possible. B is then surrounded with melting ice (as in Fig. 149) and the tube a is raised or lowered until the mercury in the arm b stands exactly opposite the fixed mark c on the tube. Now, since the space above D is a vacuum, the pressure exerted by the hydrogen in B against the mercury surface at c just supports the mercury column ED. The point D is marked on a strip of metal behind the tube a. The bulb B is then placed in a steam bath like that shown in Fig. 150. The increased pressure of the gas in B at once begins to force the mercury down at c and up at D. But by raising the arm a the mercury in b is forced back again to c, the increased pressure of the gas on the surface of the mercury at c being balanced by the increased height of the mercury column supported, which is now EF instead of ED. When the gas in B is thoroughly heated to the temperature of the steam, the arm a is very carefully adjusted so that the mercury in b stands very exactly at c, its original level. A second mark is then placed on the metal strip exactly opposite the new level of the mercury; that is, at F. Then D is marked 0° C., and F is marked 100° C. The vertical distance between these marks is divided into 100 exactly equal parts. Divisions of exactly the same length are carried above the 100° mark and below the 0° mark. One degree of change in temperature is then defined as any change in temperature which will cause the pressure of the gas in B to change by the amount represented by the distance between any two of these divisions. This distance is found to be $\frac{1}{273}$ of the height ED.

In other words, *one degree of change in temperature on the centigrade scale is such a change in temperature as will cause the pressure exerted by a confined volume of hydrogen to change by $\frac{1}{273}$ of its pressure at the temperature of melting ice (0° C.).*

170. Absolute zero and absolute temperature. Since cooling the hydrogen through 1° C., as defined above, reduces the pressure $\frac{1}{273}$ of its value at 0° C., it is clear that cooling it 273° below 0° C. would reduce its pressure to zero. But from the standpoint of the kinetic theory this would be the temperature at which all motions of the hydrogen molecules would cease. This temperature is called the *absolute zero*, and the temperature measured from this zero is called *absolute temperature*. Thus, if A is used to denote the absolute scale, we have 0° C. = 273° A., 100° C. = 373° A., 15° C. = 288° A., and so on. It is customary to indicate temperatures on the centigrade scale by t and on the absolute scale by T. We have, then,

$$T = t + 273. \qquad (1)$$

Fig. 153 gives a comparison of the absolute scale with the Fahrenheit and centigrade scales.

The mercury thermometer yields temperatures which differ from the absolute scale by an amount that is negligible for ordinary purposes (less than 2° between 0° and 100°).

171. Low temperatures. The absolute zero of temperature can, of course, never be attained, but in recent years rapid strides have been made toward it. Fifty years ago the lowest temperature which had ever been measured was $-110°$ C., the temperature attained by Faraday in 1845 by causing a mixture of ether and solid carbon dioxide to evaporate in a vacuum. But in 1880 air was first liquefied, and was found, by means of a gas thermometer, to have a temperature of $-180°$ C. When liquid air evaporates into a space which is kept exhausted by means of an air pump, its temperature falls to about $-220°$ C. Recently hydrogen has been liquefied and has been found to have a temperature at atmospheric pressure of $-243°$ C. All these temperatures have been measured by means of hydrogen thermometers. By allowing liquid hydrogen to evaporate into a space kept exhausted by an air pump, Dewar in 1900 attained a temperature of $-260°$. In 1923 Kamerlingh Onnes, using liquefied helium, attained a temperature of $-272.18°$ C., or less than 1° C. above absolute zero.

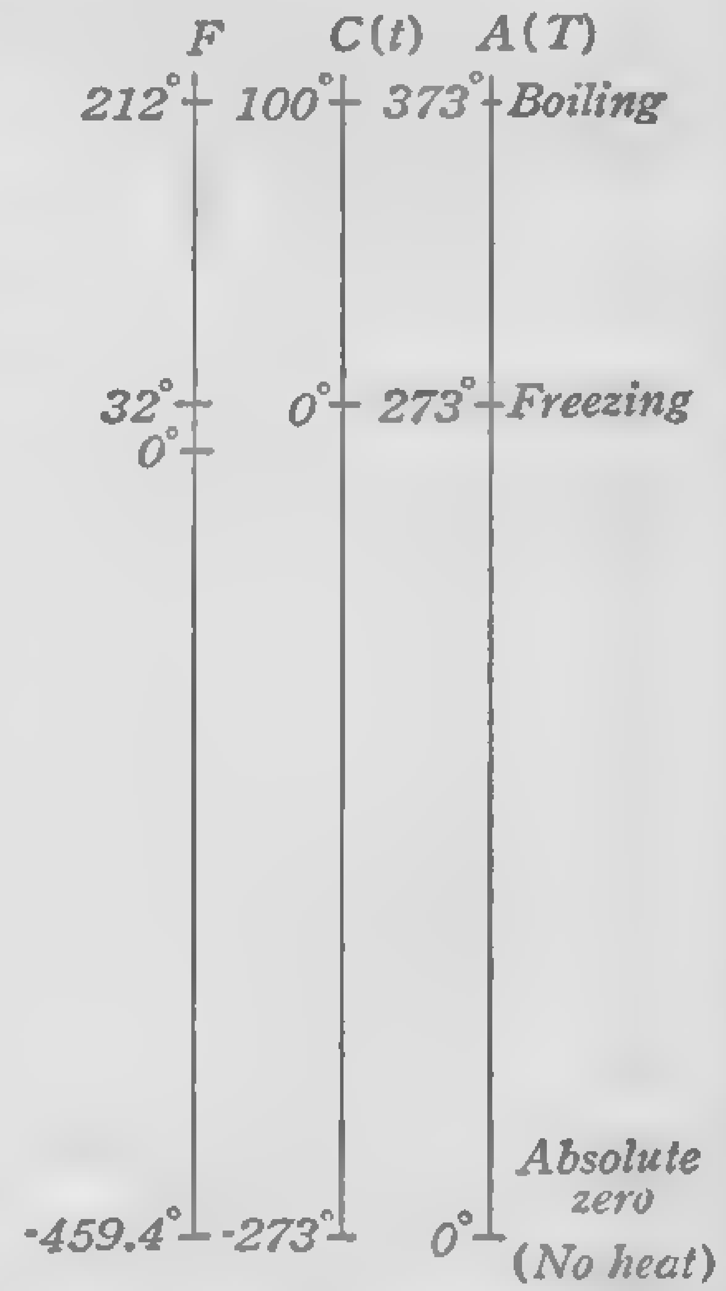


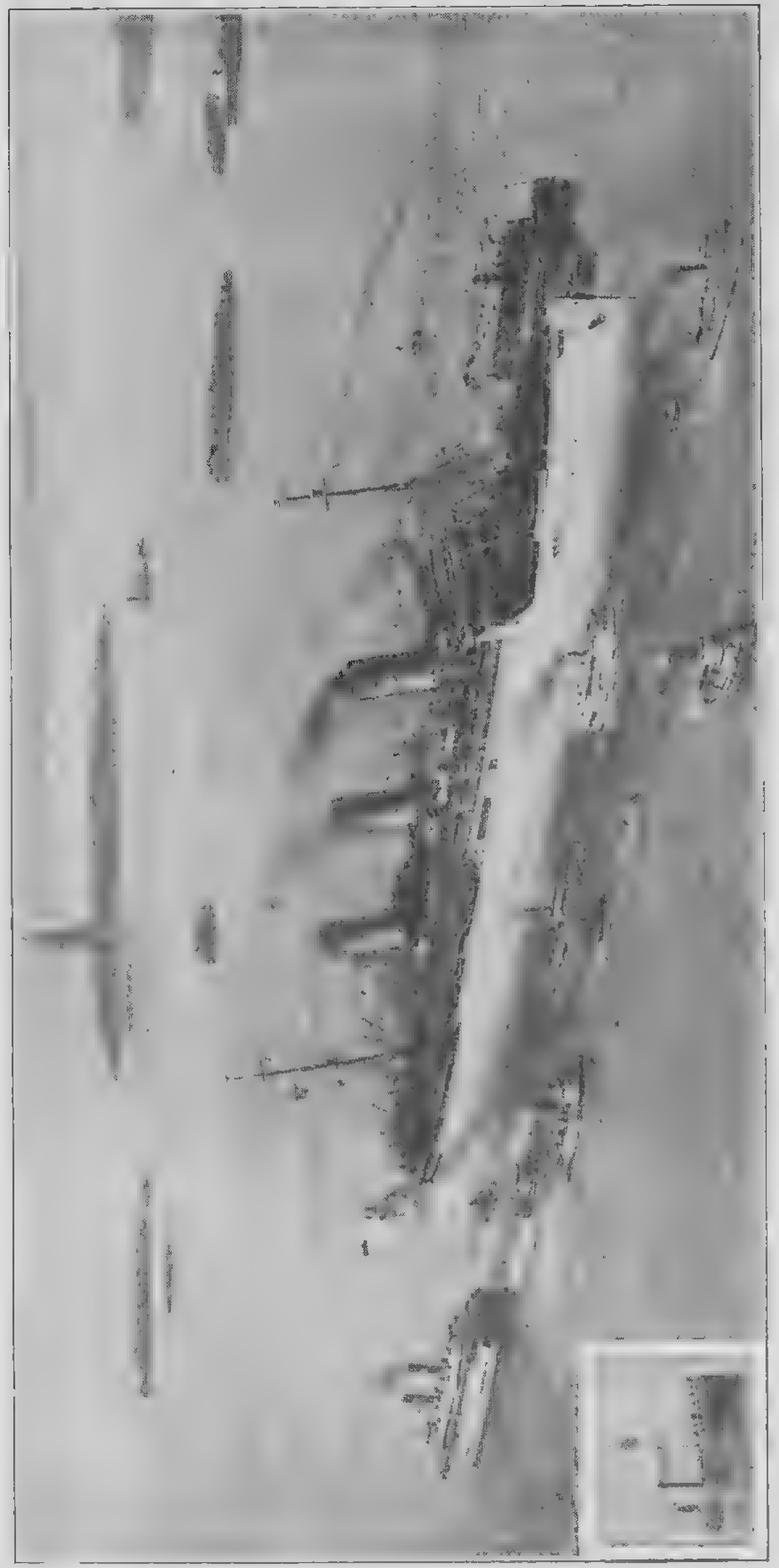
Fig. 153. Comparison of Fahrenheit, centigrade, and absolute scales

Summary. Centigrade temperatures are changed to Fahrenheit by multiplying by $\frac{9}{5}$ and adding 32.

Fahrenheit temperatures are changed to centigrade by subtracting 32 and multiplying by $\frac{5}{9}$.

LORD KELVIN (1824–1907)

One of the best known and most prolific of nineteenth-century physicists; born in Belfast, Ireland; professor of physics in Glasgow University, Scotland, for more than fifty years; especially renowned for his investigations in heat and electricity; originator of the absolute thermodynamic scale of temperature; formulator of the second law of thermodynamics; inventor of the electrometer, the mirror galvanometer, and many other important electrical devices



THE *CLERMONT* AND THE *LEVIATHAN*

This shows the relative sizes of Fulton's *Clermont*, the first successful steamboat, and the *Leviathan*, the largest ship flying the American flag. The *Clermont* was 150 feet long and 13 feet wide, and had a displacement of about 100 tons. In August, 1807, she ran from New York to Albany and back at an average speed of 5 miles per hour. The *Leviathan*, used by the United States government during the World War to transport troops, carried more than 10,000 soldiers per trip. She is 950 feet long and 100 feet wide and has a maximum displacement of 65,000 tons. She has four turbine engines, aggregating 66,000 H.P., to drive four propellers. On her trial trip she developed a speed of 25.8 knots. (Courtesy of the Times Photo Service)

One degree centigrade is such a change in temperature as causes a body of hydrogen at constant volume to change its pressure by $\frac{1}{273}$ of the pressure that it exerts at the melting point of ice (0° C.).

The absolute zero is the temperature at which all motion of the molecules of hydrogen would cease. It is 273° C. below the centigrade zero.

QUESTIONS AND PROBLEMS

1. Why is a fever thermometer made with a very long cylindrical bulb instead of a spherical one?

2. How does the distance between the 0° mark and the 100° mark vary with the cross-sectional area of the bore, the size of the bulb remaining the same?

3. Normal room temperature is 68° F. What is it centigrade?

4. What temperature centigrade corresponds to 0° F.?

5. Mercury freezes at about − 40° F. What is this centigrade?

6. The temperature of liquid air is − 180° C. What is it Fahrenheit?

7. From a study of the behavior of gases we conclude that there is a temperature at which the molecules are at rest and at which bodies therefore contain no heat. Give the reasoning that leads to this conclusion.

8. What is meant by the absolute zero of temperature?

9. Is a platinum ball at 233° C. twice as hot as when it is 20° C. below zero? Give the reason for your answer.

10. What is the absolute zero of temperature on the Fahrenheit scale?

Expansion Coefficient of Gases

172. The laws of Charles and Gay-Lussac. When, as in the experiment described in § 169, we keep the volume of a gas constant and observe the rate at which the pressure increases with the rise in temperature, we obtain *the pressure coefficient of expansion*, which is defined as *the ratio between the increase in pressure per degree and the value of the pressure at 0° C.* This was first done for different gases in 1787 by the French

chemist Charles, who found that *the pressure coefficients of expansion of all gases are the same, namely,* $\frac{1}{273}$. This is known as *the law of Charles.*

From the definition of absolute temperature (§ 170) and from Charles's law we learn that for all gases at constant volume *pressure is proportional to absolute temperature*; that is,

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}. \tag{2}$$

When we arrange the experiment so that the gas can expand as the temperature rises, the pressure remaining constant, we obtain *the volume coefficient of expansion,* which is defined as *the ratio between the increase in volume per degree and the total volume of the gas at 0° C.* This was first done for different gases in 1802 by another Frenchman, Gay-Lussac, who found that *all gases have the same volume coefficient of expansion,* this coefficient being the same as the pressure coefficient, namely, $\frac{1}{273}$. This is known as *the law of Gay-Lussac.*

From Gay-Lussac's law we learn that for all gases at constant pressure *volume is proportional to absolute temperature*; that is,

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}. \tag{3}$$

If pressure, temperature, and volume all vary, we have

$$\frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2}.* \tag{4}$$

Any one of these six quantities may be found if the other five are known.

If the volume remains constant, that is, if $V_1 = V_2$, equation (4) reduces to (2); that is, to Charles's law. If the pressure remains constant, $P_1 = P_2$ and equation (4) reduces to

* If this is not clear to the student, let him recall that if the speeds of two runners are the same, then their distances are proportional to their times, that is, $D_1/D_2 = t_1/t_2$; but if their times are the same and their speeds different, $D_1/D_2 = s_1/s_2$. If, now, one runs both twice as fast and twice as long, he evidently goes four times as far; that is, if time and speed both vary, $D_1/D_2 = t_1 s_1/t_2 s_2$.

(3); that is, to Gay-Lussac's law. If the temperature does not change, $T_1 = T_2$ and equation (4) reduces to $P_1 V_1 = P_2 V_2$; that is, to Boyle's law. If the ratio of densities instead of volumes is sought, it is only necessary to replace V_1/V_2 in (3) and (4) by D_2/D_1.

SUMMARY. ***The law of Charles.*** **The pressure coefficients of expansion of all gases are the same and are equal to** $\frac{1}{273}$.

The law of Gay-Lussac. **The volume coefficients of expansion of all gases are the same and are equal to** $\frac{1}{273}$.

QUESTIONS AND PROBLEMS

1. How is gas pressure explained by the kinetic theory of matter?

2. Why is it unsafe to let a pneumatic inkstand like the one in Fig. 486, remain in the sun?

3. To what temperature must a cubic foot of gas initially at 0° C. be raised in order to double its volume, the pressure remaining constant?

4. If the volume of a quantity of air at 30° C. is 200 cc., at what temperature will its volume be 300 cc., the pressure remaining the same?

5. The air in an automobile tire exerts a pressure of 4 kg. per square centimeter at a temperature of 10° C. To what temperature must this air rise to exert a pressure of 4.5 kg. per square centimeter, assuming that the volume of the tire does not increase?

6. If the pressure to which 15 cc. of air is subjected changes from 76 cm. to 40 cm., the temperature remaining constant, what does its volume become (see Boyle's law, p. 40)? If the temperature of the same gas then changes from 15° C. to 100° C., the pressure remaining constant, what will be the final volume?

7. The air within a half-inflated balloon occupies a volume of 100,000 l. The temperature is 15° C. and the barometric height is 75 cm. What will be its volume after the balloon has risen to the height of Mt. Blanc, where the pressure is 37 cm. and the temperature is −10° C.?

8. From the law of Gay-Lussac should you infer that the volume of a body of gas becomes nothing at the absolute zero? If not, state why.

Expansion of Liquids and Solids

173. Expansion of liquids. The expansion of liquids differs from that of gases in the following respects:

a. The coefficients of expansion of liquids are all considerably smaller than those of gases.

b. Different liquids expand at wholly different rates; for example, the coefficient of alcohol between 0° and 10° C. is .0011; of ether it is .0015; of petroleum, .0009; of mercury, .000181.

c. The same liquid often has different coefficients at different temperatures; that is, the expansion is irregular. Thus, if the coefficient of alcohol is obtained between 0° and 60° C., instead of between 0° and 10° C., it is .0013 instead of .0011.

The coefficient of mercury, however, is very nearly constant through a wide range of temperature, which, indeed, might have been inferred from the fact that mercury thermometers agree so well with gas thermometers.

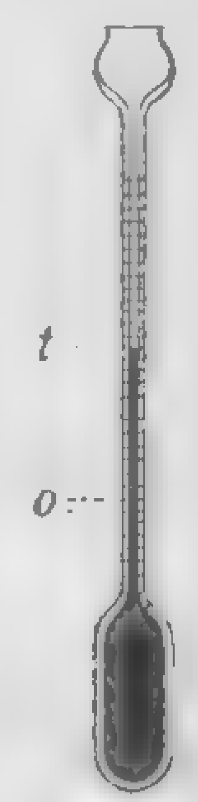


Fig. 154. Bulb for investigating expansions of liquid

174. Methods of measuring the expansion coefficients of liquids. One of the most convenient and common methods of measuring the expansion coefficients of liquids is to place the liquids in bulbs of known volume provided with capillary necks of known diameter, like the one shown in Fig. 154, and then to watch the rise of the liquid in the neck for a given rise in temperature. A certain allowance must be made for the increase in volume of the bulb, but this can readily be done if the coefficient of expansion of the substance of which the bulb is made is known.

175. Maximum density of water. When water is treated in the way described in the preceding paragraph, it reaches its lowest position in the stem at 4° C. As the temperature falls from that point down to 0° C., water exhibits the peculiar property of *expanding* with a *decrease* in temperature.

We learn, therefore, that *water has its maximum density at a temperature of 4° C.*

176. The cooling of a lake in winter. The preceding paragraph makes it easy to understand the cooling of any large body of water with the approach of winter. The surface layers are first cooled and contract. Being then heavier than the lower layers, they sink and are replaced by the warmer water from beneath. This process of cooling at the surface and sinking goes on until the whole body of water has reached a temperature of 4° C. After this condition has been reached, further cooling of the surface layers makes them *lighter* than the water beneath, and they now remain on top until they freeze (Fig. 155). Consequently, before any ice whatever can form on the surface of a lake, the whole mass of water to the very bottom must be cooled to 4° C. This is why it requires a much longer and more severe period of cold to freeze deep bodies of water than to freeze shallow bodies. Furthermore, since the circulation described above ceases at 4° C., practically all the unfrozen water will be at 4° C. even in the coldest weather. Only the water which is in the immediate neighborhood of the ice will be lower than 4° C. This fact is of vital importance in the preservation of aquatic life.

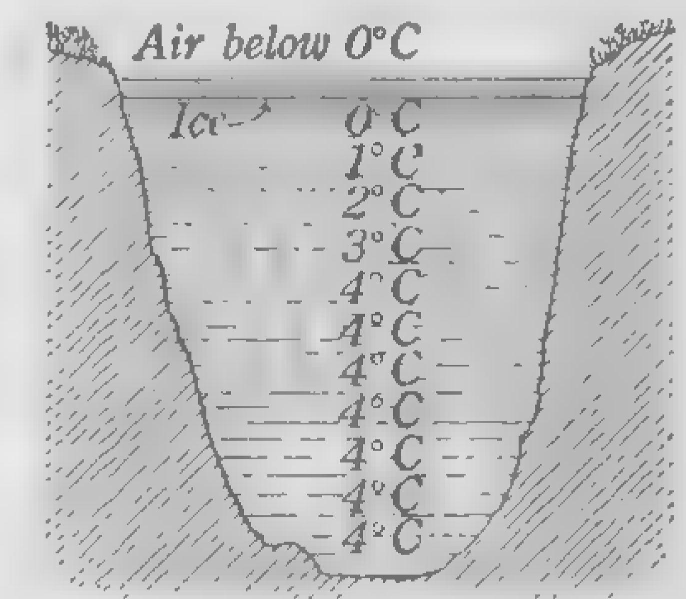


Fig. 155. Freezing of a deep lake

177. Expansion of solids. Proofs of the expansion of solids with an increase in temperature may be seen on every side. Railroad rails are laid with spaces between their ends so that they may expand during the heat of summer without crowding each other out of place. Wagon tires are made smaller than the wheels which they are to fit. They are then heated until they become large enough to be driven on, and in cooling they shrink again and thus grip the wheels with immense

force. A common lecture-room demonstration of expansion is the following:

Let the ball B, which when cool just slips through the ring R, be heated in a Bunsen flame. It will now be found too large to pass through the ring; but if the ring is heated, or if the ball is again cooled, it will pass through easily (see Fig. 156).

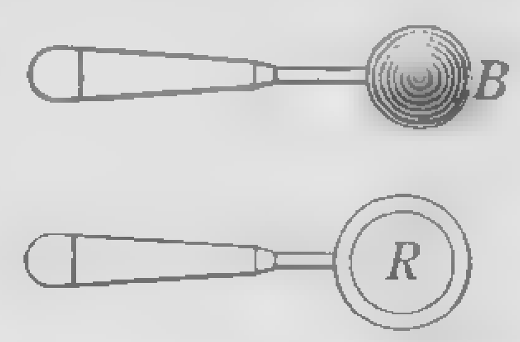


FIG. 156. Expansion of solids

If the expansion of gases and liquids is caused by an increase in the average kinetic energy of agitation of their molecules, the foregoing experiments with solids must clearly be given a similar interpretation. In a word, then, the temperature of a given substance, be it a solid, a liquid, or a gas, is determined by the average kinetic energy of agitation of its molecules.

178. Linear coefficients of expansion of solids. It is often more convenient to measure the increase in *length* of one edge of an expanding solid than to measure its increase in *volume*. *The ratio of the increase in length per degree rise in temperature to the total length is called the linear coefficient of expansion of the solid.* Thus, if l_1 represents the length of a bar at $t_1°$, and l_2 its length at $t_2°$, the equation which defines the linear coefficient k is

$$k = \frac{\frac{l_2 - l_1}{t_2 - t_1}}{l_1} = \frac{l_2 - l_1}{l_1(t_2 - t_1)}. \tag{5}$$

Otherwise stated, *change in length = coefficient of expansion × length × change in temperature*, or

$$l_2 - l_1 = kl_1(t_2 - t_1). \tag{6}$$

The difference in linear coefficients of expansion of different substances may be illustrated as follows:

The bar of Fig. 157 consists of two strips, one of brass and one of iron, riveted together. Let the bar be placed edgewise in a Bunsen flame so that both metals are heated equally. The bar

bends as indicated in Fig. 158, showing that the more expansible metal, the brass, is on top. Let the bar be plunged into snow or ice to bend in the opposite direction.

FIG. 157

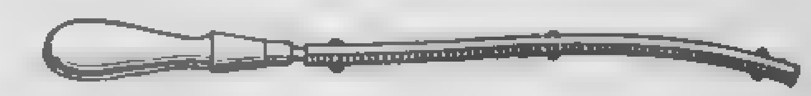


FIG. 158

Unequal expansion of metals

The linear coefficients of a few common substances are given in the following table:

"Invar" steel ($\frac{3}{10}$ nickel)	.0000009	Copper	.000017
Glass (pyrex)	,000003	Brass	.000019
Glass (ordinary)	.000009	Silver	.000019
Platinum	.000009	Aluminum	.000023
Iron	.000012	Lead	.000029
Steel	.000013	Zinc	.000029
Nickel	.000013	Sodium	.000226

APPLICATIONS OF EXPANSION

179. Compensated balance wheel. In the balance wheel of an accurate watch (Fig. 159) another application of the unequal expansion of metals is made. Increase in temperature both increases the radius of the wheel and weakens the elasticity of the spring which controls it. Both these effects tend to make the watch lose time. This tendency may be counteracted by bringing the mass of the rotating parts in toward the center of the wheel. This is accomplished by making the arcs bc of metals of different expansion coefficients, the inner metal (shown in black in the figure) having the smaller coefficient. The free ends of the arcs are then sufficiently pulled in by a rise in temperature to counteract the retarding effects. The principle is precisely the same as that which was simply illustrated in the compound bar shown in Fig. 157.

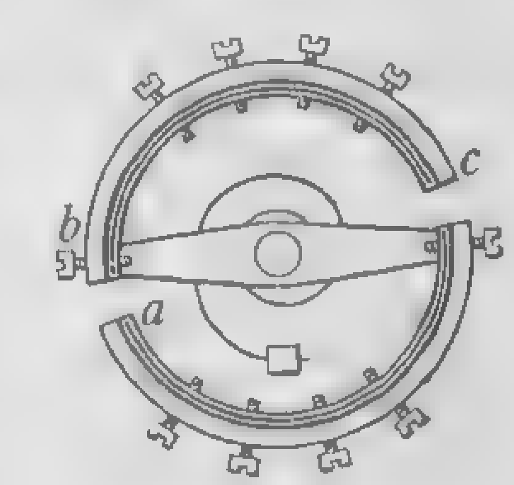


FIG. 159. The compensated balance wheel

The common thermostat (Fig. 160) is a compound bar of brass and invar steel so arranged as to open the drafts by closing an electrical circuit at a when it is too cold and to close the drafts by making contact at b when it is too warm.

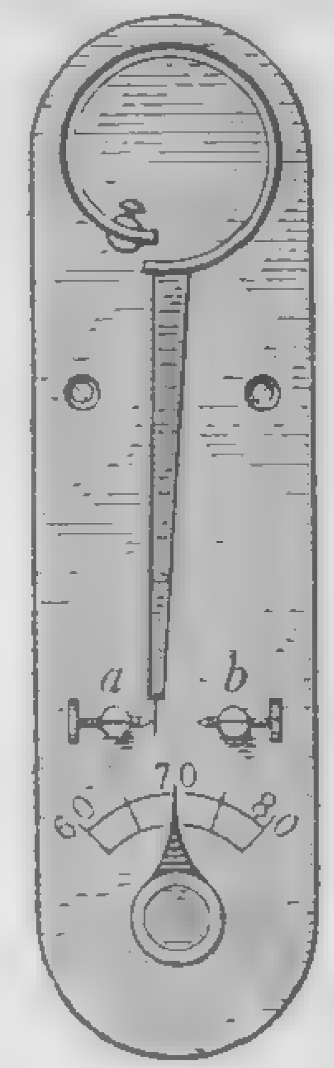


FIG. 160. The thermostat

SUMMARY. The volume coefficient of expansion of any substance is the ratio of the increase in volume per degree rise in temperature to the initial volume (strictly the volume at zero).

The linear coefficient of expansion of a solid is the ratio of the increase in length per degree and the initial length (strictly the length at zero).

Differences in the coefficients of expansion of different solids are made use of in a variety of ways: for control of timepieces, for temperature regulation, for measurement of temperature, and so on.

QUESTIONS AND PROBLEMS*

1. Why is a thick tumbler more likely to break when hot water is poured into it than a thin one?

2. Why does pyrex glass (oven glass) not break when suddenly removed from the oven to a cold table.

3. Chemical vessels (beakers, test tubes, dishes, etc.) are sometimes made of pure quartz. They may be heated red-hot and then plunged into water without breaking. How do you account for this?

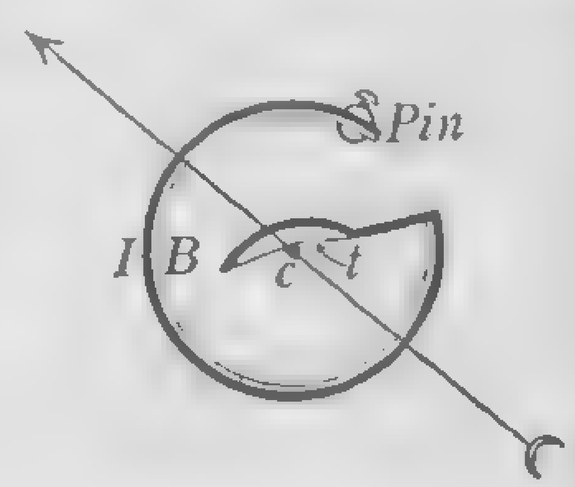


FIG. 161

4. Give three reasons why mercury is a better liquid to use in thermometers than water.

5. Why may a glass stopper sometimes be loosened by pouring hot water on the neck of a bottle?

6. The dial thermometer is a compound bar (Fig. 161) with iron on the outside and brass on the inside. A thread t is wound about the central cylinder c. Explain the action.

* Supplementary questions and problems for Chapter VIII are given in the Appendix.

7. The steel cable from which Brooklyn Bridge hangs is more than a mile long. By how many feet does a mile of its length vary between a winter day when the temperature is $-20°$ C. and a summer day when it is 30° C.?

8. The changes in temperature to which long lines of steam pipes are subjected make it necessary to introduce "expansion joints." These joints consist of brass collars fitted tightly by means of packing over the separated ends of two adjacent lengths of pipe. If the pipe is of iron, and such a joint is inserted every 200 ft., and if the range of temperature which must be allowed for is from $-30°$ C. to 125° C., what is the minimum play which must be allowed for at each expansion joint?

9. If the span of a transmission line is 800 ft. long at 0° C. and 800.704 ft. long at 40° C., what is the coefficient of expansion of the wire?

CHAPTER IX

WORK AND HEAT ENERGY

Mechanical Equivalent of Heat *

180. What becomes of wasted work? In all the devices for transforming work that we have considered we have found that on account of frictional resistances a certain per cent of the work expended upon the machine is wasted. The question which at once suggests itself is, What becomes of this wasted work? The following familiar facts suggest an answer. When two sticks are vigorously rubbed together, they become hot; augers and drills often become too hot to hold; matches are ignited by friction; if a strip of lead is struck a few sharp blows with a hammer, it is appreciably warmed. Now, since we learned in Chapter VIII that, according to modern notions, increasing the temperature of a body means simply increasing the average velocity of its molecules, and therefore their average kinetic energy, the above facts point strongly to the conclusion that in each case the mechanical energy expended has been simply transformed into the energy of molecular motion. This view was first brought into prominence in 1798 by Benjamin Thompson, Count Rumford, an American by birth, who was led to it by observing that in the boring of cannon heat was continuously developed. It was first carefully tested by the English physicist James Prescott Joule (see opposite page 169) (1818–1889) in a series of epoch-making experiments extending from 1842 to 1870.

* This subject should be preceded by a laboratory experiment upon the "law of mixtures," and either preceded or accompanied by experiments upon specific heat and mechanical equivalent. See Experiments 23 and 24 in "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

In order to understand these experiments we must first learn how heat quantities are measured.

181. Units of heat: the calorie and the British thermal unit. *The calorie is the amount of heat that is required to raise the temperature of 1 gram of water through 1° C., and the British thermal unit (B.T.U.) is the amount of heat that is required to raise the temperature of 1 pound of water through 1° F.* (One B.T.U. = 252 cal.) Thus, when a hundred grams of water has its temperature raised 4° C., we say that four hundred calories of heat have entered the water. Similarly, when a hundred grams of water has its temperature lowered 10° C., we say that a thousand calories have passed out of the water. If, then, we wish to measure, for instance, the amount of heat developed in a lead bullet when it strikes against a target, we have only to let the spent bullet fall into a known weight of water and to measure the number of degrees through which the temperature of the water rises. The product of the number of grams of water by its rise in temperature is, then, by definition, the number of calories of heat which have passed into the water.

It will be noticed that in the definition above we make no assumption whatever as to *what heat is*. Previous to the nineteenth century, physicists generally held it to be an invisible, weightless fluid, the passage of which into or out of a body caused it to grow hot or cold. This view accounts well enough for the heating which a body experiences when it is held in contact with a flame or other hot body, but it has difficulty in explaining the heating produced by rubbing or pounding. Rumford's view accounts easily for this, as we have seen, and it accounts no less easily for the heating of cold bodies by contact with hot ones; for we have only to think of the hotter and therefore more energetic molecules of the hot body as communicating their energy to the molecules of the colder body in much the same way in which a rapidly moving billiard ball transfers part of its kinetic energy to a more slowly moving ball against which it strikes.

182. Joule's experiment on the heat developed by friction. Joule argued that if the heat produced by friction etc. is indeed merely mechanical energy which has been transferred to the molecules of the heated body, then the same number of calories must always be produced by the disappearance of a given amount of mechanical energy. And this must be true, no matter whether the work is expended in overcoming the friction of wood on wood, of iron on iron, in percussion, in compression, or in any other conceivable way. To see whether or not this was so he caused mechanical energy to disappear in as many ways as possible and measured in every case the amount of heat developed.

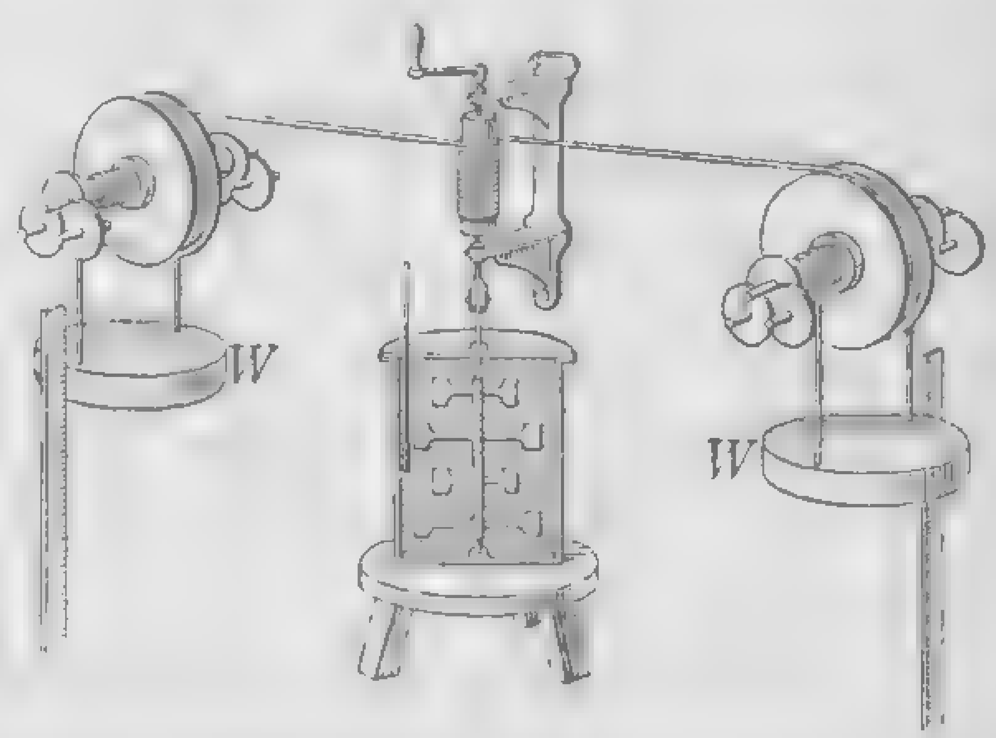


FIG. 162. Joule's first experiment on the mechanical equivalent of heat

In his first experiment he caused paddle wheels to rotate in a vessel of water by means of falling weights W (Fig. 162). The amount of work done by gravity upon the weights in causing them to descend through any distance d was equal to their weight W times this distance. If the weights descended slowly and uniformly, this work was all expended in overcoming the resistance of the water to the motion of the paddle wheels through it; that is, it was wasted in eddy currents in the water. Joule measured the rise in the temperature of the water and found that the mean of his best three trials gave *427 gram meters as the amount of work required to develop enough heat to raise a gram of water one degree. (This means that to raise a pound of water 1° F. requires the expenditure of 778 ft. lb. of work.) This value, confirmed by modern experiments, is now generally accepted as correct.* He then repeated the experiment, substituting mercury for water, and obtained 425 gram meters as the work necessary to produce a calorie of heat. The difference between these numbers is less than was to have been expected from the unavoidable errors in the observations. He then devised an arrangement in which the heat was developed by the friction of iron on iron, and again obtained 425.

183. Heat produced by collision. A Frenchman named Hirn was the first to make a careful determination of the relation between the heat developed by *collision* and the kinetic energy which disappears. He allowed a steel cylinder to fall through a known height and crush a lead ball by its impact upon it. The amount of heat developed in the lead was measured by observing the rise in temperature of a small amount of water into which the lead was quickly plunged. As the mean of a large number of trials he also found that 425 gram meters of energy disappeared for each calorie of heat that appeared.

184. Heat produced by the compression of a gas. Another way in which Joule measured the relation between heat and work was by compressing a gas and comparing the amount of work done in the compression with the amount of heat developed.

Every bicyclist is aware of the fact that when he inflates his tires the pump grows hot. This is due partly to the friction of the piston against the walls, but chiefly to the fact that the downward motion of the piston is transferred to the molecules which come in contact with it, so that the velocity of these molecules is increased. The principle is precisely the same as that involved in the velocity communicated to a ball by a bat. If the bat is held rigidly fixed and a ball thrown against it, the ball rebounds with a certain velocity; but if the bat is moving rapidly forward to meet the ball, the latter rebounds with a much greater velocity. So the molecules which in their natural motions collide with an advancing piston rebound with greater velocity than they would if they had impinged upon a fixed wall. This increase in the molecular velocity of a gas on compression is so great that when a mass of gas at 0° C. is compressed to one half its volume, the temperature rises to 87° C.

The effect may be strikingly illustrated by the fire syringe (Fig. 163). Let a few drops of carbon bisulphide be placed on a small bit of cotton, dropped to the bottom of the tube A, and then

removed; then let the piston B be inserted and very suddenly depressed. Sufficient heat will be developed to ignite the vapor, and a flash will result. (If the flash does not result from the first stroke, withdraw the piston completely, then reinsert, and compress again.)

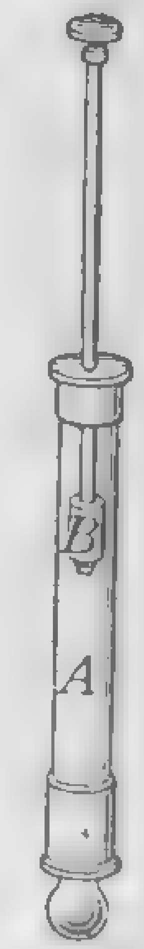


FIG. 163. The fire syringe

To measure the heat of compression Joule surrounded a small compression pump with water, made 300 strokes on the pump, and measured the rise in temperature of the water. As the result of these measurements he obtained 444 gram meters as the mechanical equivalent of the calorie. The experiment, however, could not be performed with great exactness.

Joule also measured the converse effect, namely, the cooling produced in a gas which is pushing forward a piston and thus *doing work*. He obtained 437 gram meters.

185. Significance of Joule's experiments. Joule made three other determinations of the relation between heat and work by methods involving electrical measurements. He published as the mean of all his determinations 426.4 gram meters as the mechanical equivalent of the calorie. But the value of his experiments does not lie primarily in the accuracy of the final results, but rather in the proof which they for the first time furnished that *whenever a given amount of work is wasted, no matter in what particular way this waste occurs, the same definite amount of heat always appears.*

The most accurate determination of the mechanical equivalent of heat was made by Rowland (see opposite page 390) (1848–1901) in 1880. *He obtained 427 gram meters* (4.19×10^7 *ergs*). We shall generally take it as 42,000,000 ergs. *The mechanical equivalent of 1 B.T.U.* is *778 foot pounds.*

186. Conservation of energy. We are now in a position to state the law of all machines in its most general form, that is, in such a way as to include even the cases where friction is present. It is: *The work done by the acting force is equal*

to the sum of the kinetic and potential energies stored up plus the mechanical equivalent of the heat developed.

In other words, *whenever energy is expended on a machine or device of any kind, an exactly equal amount of energy always appears either as useful work or as heat.* The useful work may be represented in the potential energy of a lifted mass, as when water is pumped up to a reservoir; or in the kinetic energy of a moving mass, as when a stone is thrown from a sling; or in the potential energies of molecules whose positions with reference to one another have been changed, as when a spring has been bent; or in the molecular potential energy of chemically separated atoms, as when an electric current separates a compound substance. The *wasted* work always appears in the form of increased molecular motion, that is, in the form of heat. This important generalization has received the name of the *principle of the conservation of energy.* It may be stated thus: *Energy may be transformed, but it can never be created or destroyed.*

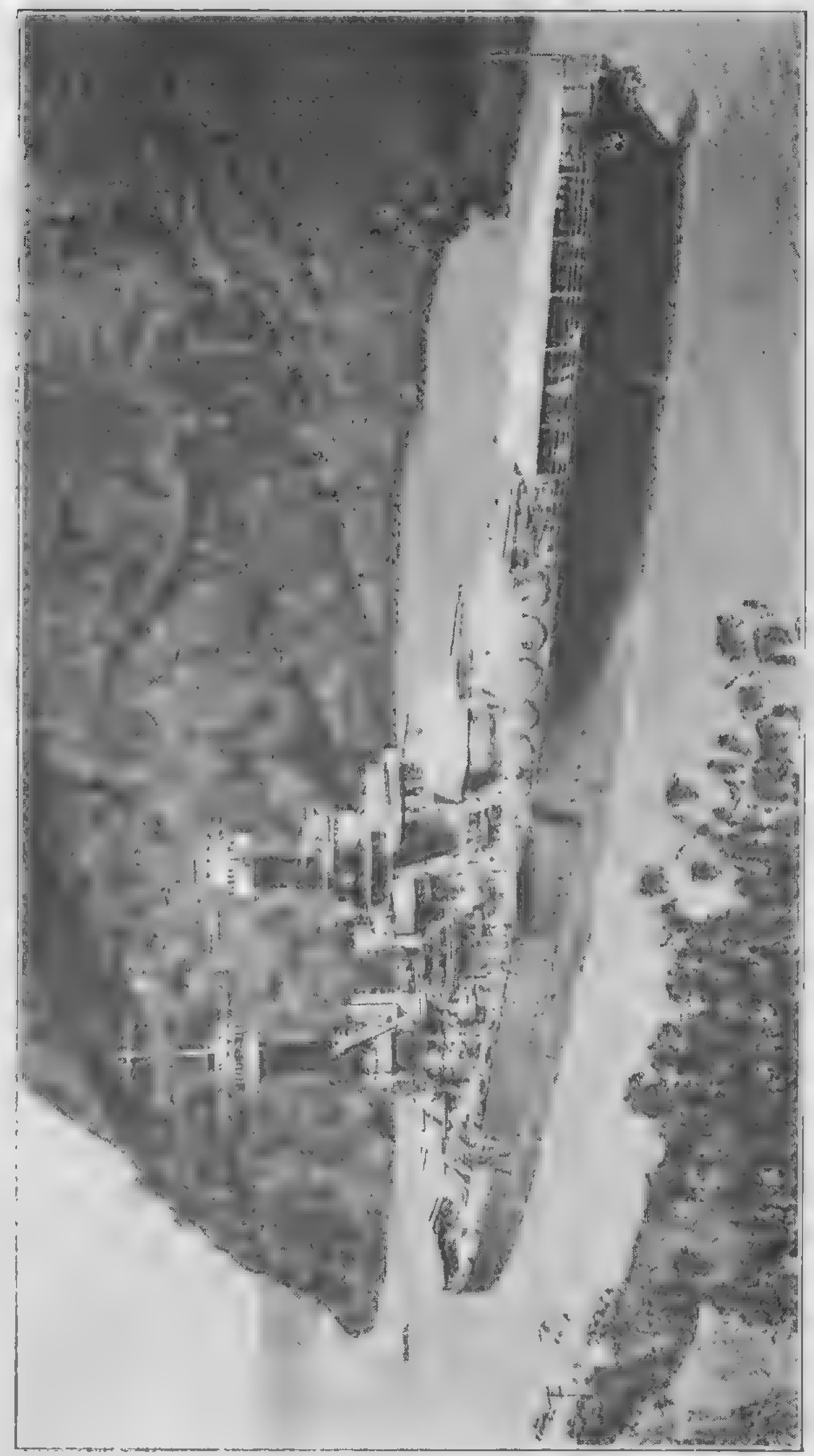
187. Perpetual-motion machines. In all ages there have been men who tried to invent a machine out of which work could be continually obtained, without the expenditure of an equivalent amount of work upon it; that is, a perpetual-motion machine. The possibility of the existence of such a device is absolutely denied by the statement of the principle of the conservation of energy. For only in case there is no heat developed, that is, in case there are no frictional losses, can the work taken out be equal to the work put in, and in no case can it be greater. Since, in fact, there are always some frictional losses, the principle of the conservation of energy asserts that it is impossible to make a machine which will keep itself running forever, even though it does no useful work; for no matter how much kinetic or potential energy is imparted to the machine to begin with, there must always be a continual drain upon this energy to overcome frictional resistances, so that as soon as the wasted work has become equal to the initial energy, the machine must stop.

The principle of the conservation of energy has now gained universal recognition and has taken its place as the corner stone of all physical science. Einstein (see opposite page 54) has recently suggested, however, that matter and energy may be interconvertible, and there is some evidence in favor of this view.

188. Transformations of energy in a power plant. The transformations of energy which take place in any power plant, such as that at Niagara, are as follows: The energy first exists as the potential energy of the water at the top of the falls. This is transformed in the turbine pits into the kinetic energy of the rotating wheels. These turbines drive dynamos in which there is a transformation into the energy of electric currents. These currents travel on wires as far as Syracuse, 150 miles away, where they run street cars and other forms of motors. The principle of conservation of energy asserts that the work which gravity did upon the water in causing it to descend from the top to the bottom of the turbine pits is exactly equal to the work done by all the motors, plus the heat developed in all the wires and bearings and in the eddy currents in the water.

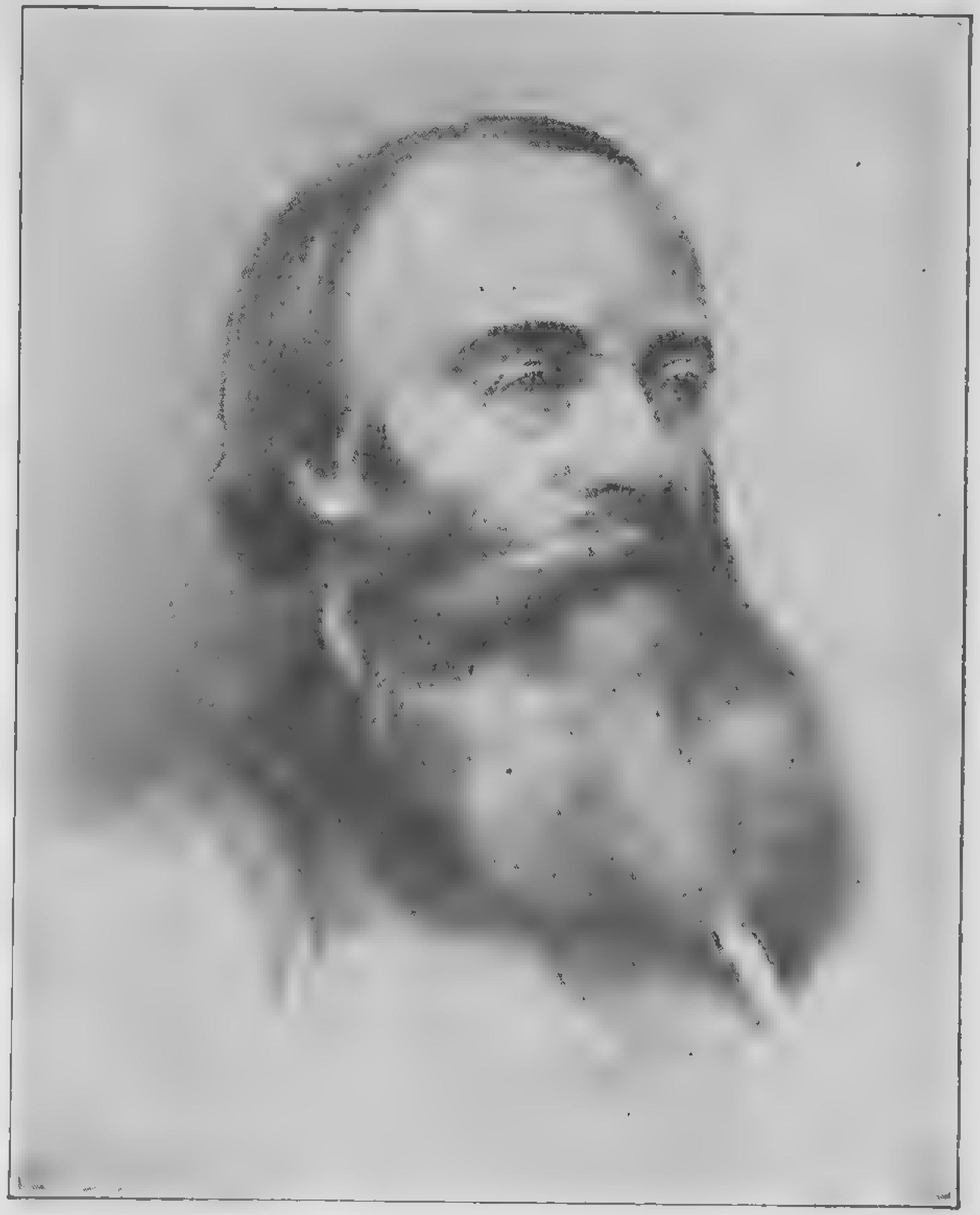
Let us next consider where the water at the top of the falls obtained its potential energy. Water is being continually evaporated at the surface of the ocean by the sun's heat. This heat imparts sufficient kinetic energy to the molecules to enable them to break away from the attractions of their fellows and to rise above the surface in the form of vapor. The lifted vapor is carried by winds over the continents and precipitated in the form of rain or snow. Thus the potential energy of the water above the falls at Niagara is simply transformed heat energy of the sun. If in this way we analyze any available source of energy at man's disposal, we find in almost every case that it is directly traceable to the sun's heat as its source. Thus, the energy contained in coal is simply the energy of separation of the oxygen and carbon which were separated in the processes of growth. This separation was effected by the sun's rays.

The earth is continually receiving energy from the sun at the rate of 342,000,000,000,000 horse power, or about one fifth of a million horse power per inhabitant. We can form some conception of the enormous amount of energy that the sun radiates in the form of heat by reflecting that the amount received by the earth



A UNITED STATES DREADNAUGHT PASSING THROUGH THE FAMOUS GAILLARD CUT OF THE PANAMA CANAL

A superdreadnaught of the *Maryland* type, the largest in use, has a displacement of over 33,600 tons and a horse power of about 33,000, and develops a speed of about 21 knots. She carries eight 16-inch guns which throw 2040-pound projectiles effectively against an enemy ship 15 to 20 miles distant. One shot from a 16-inch gun has an energy equivalent of 98,406 foot tons (= 196,182,000 foot pounds). The penetrating power of these new 16-inch guns is 32 inches of the hardest armor plate



JAMES PRESCOTT JOULE (1818-1889)

English physicist, born at Manchester; most prominent figure in the establishment of the doctrine of the conservation of energy; studied chemistry as a boy under John Dalton, and became so interested that his father, a prosperous Manchester brewer, fitted out a laboratory for him at home; conducted most of his researches either in a basement of his own house or in a yard adjoining his brewery; discovered the law of heating a conductor by an electric current; carried out, in connection with Lord Kelvin, epoch-making researches upon the thermal properties of gases; did important work in magnetism; first proved experimentally the identity of various forms of energy

is not more than $\frac{1}{2,000,000,000}$ of the total given out. Of the amount received by the earth not more than $\frac{1}{1000}$ part is stored up in animal and vegetable life and lifted water. This is practically all the energy which is available on the earth for man's use.

SUMMARY. Joule proved that heat has a mechanical equivalent by experimentally showing that whenever a given amount of work is transformed into heat, no matter in what particular way this transformation occurs, the same definite amount of heat always appears.

The mechanical equivalent of 1 calorie is 427 gram meters (= 42,000,000 ergs).

The mechanical equivalent of 1 B.T.U. is 778 foot pounds.

General law of all machines where friction is present and velocity imparted to mass. The work done by the acting force is equal to the sum of the kinetic and potential energies stored up plus the mechanical equivalent of the heat developed; or, whenever energy is expended on a machine or device of any kind, an exactly equal amount of energy always appears either as useful work or as heat.

QUESTIONS AND PROBLEMS

1. A golf ball weighing 45 g. dropped 200 cm. on a marble step and rebounded 150 cm. How many gram centimeters of mechanical energy disappeared? Into what form of energy did it change, and where was this energy located?

2. Explain the fact that the principle of conservation of energy could not have been discovered before means were devised to measure heat.

3. The kinetic energy of mass motion of an automobile running 20 mi. per hour was 37,344 ft. lb. In stopping this car how many B. T. U. were developed in the brakes?

4. Two and a half gallons of water (= 20 lb.) were warmed from 68° F. to 212° F. If the heat energy put into the water could all have been made to do useful work, how high could 10 t. of coal have been hoisted?

5. Explain why the cylinder of an automobile-tire pump becomes hot when the pump is being used? Why is the air cooled as it escapes from the valve of an automobile tire?

6. Show that the principle of conservation of energy makes it necessary that a body of gas should cool on expanding.

Specific Heat

189. Definition of specific heat. When we experiment upon different substances, we find that it requires wholly different amounts of heat energy to produce in one gram of mass one degree of change in temperature.

Let 100 g. of lead shot be placed in one test tube, 100 g. of bits of iron wire in another, and 100 g. of aluminum wire in a third. Let them all be placed in a pail of boiling water for ten or fifteen minutes, care being taken not to allow any of the water to enter any of the tubes. Let three small vessels be provided, each of which contains 100 g. of water at the temperature of the room. Let the heated shot be poured into the first beaker, and after thorough stirring let the rise in the temperature of the water be noted. Let the same be done with the other metals. The aluminum will be found to raise the temperature about twice as much as the iron, and the iron about three times as much as the lead. Hence, since the three metals have cooled through approximately the same number of degrees, we must conclude that about six times as much heat has passed out of the aluminum as out of the lead; that is, each gram of aluminum in cooling 1° C. gives out about six times as many calories as a gram of lead.

The number of calories taken up by 1 gram of a substance when its temperature rises through 1° C., or given up when it falls through 1° C., is called the specific heat of that substance.

It will be seen from this definition, and the definition of the calorie, that the specific heat of water is 1.

190. Determination of specific heat by the method of mixtures. The preceding experiments illustrate a method for measuring accurately the specific heats of different substances; for, in accordance with the principle of the conservation of energy, when hot and cold bodies are mixed, as in these experiments, so that heat energy passes from one to the other, *the gain in the heat energy of one must be just equal to the loss in the heat energy of the other.*

This method is by far the most common one for determining specific heats. It is known as the *method of mixtures.*

Suppose, to take an actual case, that the initial temperature of the shot used in § 189 was 95° C. and that of the water 19.7°, and that, after mixing, the temperature of the water and shot was 22°. Then, since 100 g. of water has had its temperature raised through $22° - 19.7° = 2.3°$, we know that 230 calories of heat have entered the water. Since the temperature of the shot fell through $95° - 22° = 73°$, the number of calories given up by the 100 g. of shot in falling 1° was $\frac{230}{73} = 3.15$. Hence the specific heat of lead, that is, *the number of calories of heat given up by 1 gram of lead when its temperature falls 1° C.*, is $3.15/100 = .0315$.

Or, again, we may work out the problem algebraically as follows: Let x equal the specific heat of lead. Then the number of calories which come out of the shot is *its mass times its specific heat times its change in temperature*, that is, $100 \times x \times (95 - 22)$; and, similarly, the number which enter the water is the same, namely, $100 \times 1 \times (22 - 19.7)$. Hence we have

$$100\,(95 - 22)\,x = 100\,(22 - 19.7), \text{ or } x = .0315.$$

By experiments of this sort the specific heats of some of the common substances have been found to be as follows:

TABLE OF SPECIFIC HEATS

Lead	.0315	Copper	.095
Gold	.0316	Iron	.113
Platinum	.032	Glass	.2
Mercury	.0333	Earth, rock, sand (about)	.2
Silver	.0568	Aluminum	.218
Brass	.094	Ice	.504

Summary. **The specific heat of a substance is the number of calories taken up by 1 gram of the substance when its temperature rises through 1° C.**

The number of heat units lost or gained by a body equals its mass times its change in temperature times its specific heat.

Determination of the specific heat by the method of mixtures is made by equating heat lost by the cooling body to heat gained by the warming body.

QUESTIONS AND PROBLEMS *

1. Why is a liter of hot water a better foot warmer than an equal weight of any substance in the preceding table?

2. The specific heat of water is much greater than that of any other liquid or of any solid. Explain how this accounts for the fact that an island in mid-ocean undergoes less extremes of temperature than an inland region.

3. A barrelful of tepid water, when poured into a snowdrift, melts much more snow than a cupful of boiling water does. Which has the greater quantity of heat?

4. Which would be heated more, a lead or a steel bullet, if they were fired against a target with equal speeds?

5. How many calories are required to heat a laundry iron weighing 3 kg. from 20° C. to 130° C.?

6. How many B.T.U. are required to heat a 6-pound fireless-cooker stone from 68° F. to 500° F. (specific heat of soapstone = .2)?

7. If 100 g. of mercury at 95° C. are mixed with 100 g. of water at 15° C., and if the resulting temperature is 17.6° C., what is the specific heat of mercury?

8. If 200 g. of water at 80° C. are mixed with 100 g. of water at 10° C., what will be the temperature of the mixture? (Let x equal the final temperature; then $100 (x - 10)$ calories are gained by the cold water, while $200 (80 - x)$ calories are lost by the hot water.)

9. What temperature will result if 400 g. of aluminum at 100° C. are placed in 500 g. of water at 20° C.?

10. A piece of platinum weighing 10 g. is taken from a furnace and plunged instantly into 40 g. of water at 10° C. The temperature of the water rises to 24° C. What was the temperature of the furnace?

* Supplementary questions and problems for Chapter IX are given in the Appendix.

CHAPTER X

CHANGE OF STATE

FUSION *

191. Heat of fusion. If on a cold day in winter a quantity of snow is brought in from out of doors, where the temperature is below 0° C. and placed over a source of heat, a thermometer plunged into the snow will be found to rise slowly until the temperature reaches 0°C., when it will become stationary and remain so during all the time the snow is melting, provided only that the contents of the vessel are continuously and vigorously stirred. As soon as the snow is all melted, the temperature will begin to rise again.

Since the temperature of ice at 0° C. is the same as the temperature of water at 0° C., it is evident from this experiment that when ice is being changed to water, the entrance of heat energy into it does not produce any change in the average kinetic energy of its molecules. This energy must therefore all be expended in pulling apart the molecules of the crystals of which the ice is composed, and thus reducing it to a form in which the molecules are held together less intimately, that is, to the liquid form. In other words, the energy which existed in the flame as the kinetic energy of molecular motion has been transformed, upon passage into the melting solid, into the potential energy of molecules which have been pulled apart against the force of their mutual attraction. *The number of calories of heat energy required to melt one gram of any substance without producing any change in its temperature is called the heat of fusion of that substance.*

* This subject should be preceded by a laboratory exercise on the curve of cooling through the point of fusion, and followed by a determination of the heat of fusion of ice. See, for example, Experiments 25 and 26 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

192. Numerical value of heat of fusion of ice. Since it is found to require about 80 times as long for a given flame to melt a quantity of snow as to raise the melted snow through 1° C., we conclude that it requires about 80 calories of heat to melt 1 g. of snow or ice. This constant is, however, much more accurately determined by the method of mixtures. Thus, suppose that a piece of ice weighing 131 g. is dropped into 500 g. of water at 40° C., and suppose that after the ice is all melted the temperature of the mixture is found to be 15° C. The number of calories which have come out of the water is $500 \times (40 - 15) = 12{,}500$. But $131 \times 15 = 1965$ calories of this heat must have been used in raising the water from the melted ice from 0° C. to 15° C. The remainder of the heat, namely, $12{,}500 - 1965 = 10{,}535$, must have been used in melting the 131 g. of ice. Hence the number of calories required to melt 1 g. of ice is $\frac{10535}{131} = 80.4$.

To state the problem algebraically, let $x =$ the heat of fusion of ice. Then we have

$$131\,x + 1965 = 12{,}500; \text{ that is, } x = 80.4.$$

According to the most careful determinations the heat of fusion of ice is 80.0 calories.

193. Energy transformation in fusion. The heat energy that goes into a body to change it from the solid state to the liquid state no longer exists as heat within the liquid. It has *ceased to exist as heat energy at all,* having been transformed into *molecular potential energy*; that is, *the heat which disappears represents the work that was done in effecting the change of state,* and it is, therefore, the exact equivalent of the potential energy gained by the rearranged molecules. This is strictly in accord with the law of conservation of energy.

194. Heat given out when water freezes. Let snow and salt be added to a beaker of water until the temperature of the liquid mixture is as low as − 10° C. or − 12° C. Then let a test tube containing a thermometer and a quantity of pure water be thrust into the cold solution. If the thermometer is kept very quiet, the temperature of the water in the test tube will fall four or five or even ten degrees below 0° C. without producing solidification. But as soon as the thermometer is stirred, or a small crystal of ice is dropped into the neck of the tube, the ice crystals will form with great suddenness, and at the same time the thermometer will rise to 0° C., where it will remain until all the water is frozen.

The experiment shows in a very striking way that the process of freezing is a heat-evolving process. This was to have been expected from the principle of the conservation of energy; for *since it takes 80 calories of heat energy to turn a gram of ice at 0° C. into water at 0° C., this amount of energy must reappear when the water turns back to ice.*

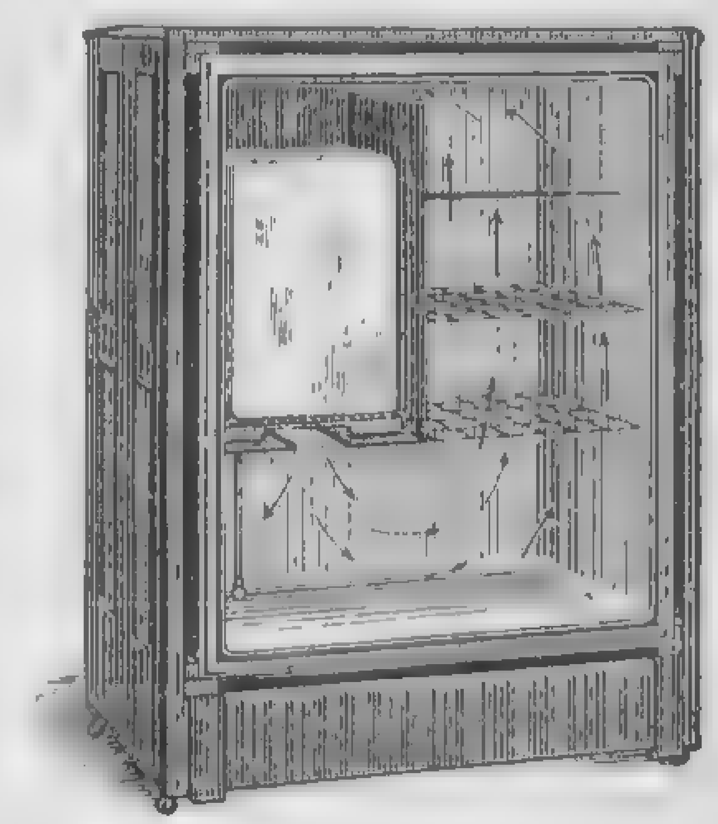


FIG. 164. A refrigerator

195. Use made of energy transformations in melting and freezing. A refrigerator (Fig. 164) is a box constructed with double walls so as to make it difficult for heat to pass in from the outside. Ice is kept in the *upper* part of one compartment so as to cool the air at the top, which, because of its greater density when cool, settles and causes a circulation as indicated by the arrows. For each gram of ice that melts 80 calories disappear from the air and food within the refrigerator.

The heat given off by the freezing of water is often turned to practical account; for example, tubs of water are sometimes placed in vegetable cellars to prevent the vegetables from freezing. The effectiveness of this procedure is due to the fact that the temperature at which the vegetables freeze is slightly lower than 0° C. As the temperature of the cellar falls the water therefore begins to freeze first, and in so doing evolves enough heat to prevent the freezing of the vegetables.

It is partly because of the heat evolved by the freezing of large bodies of water that the temperature never falls so low in the vicinity of large lakes as it does in inland localities.

196. Melting points of crystalline substances. If a piece of ice is placed in a vessel of boiling water for an instant and then removed and wiped, it will not be found to be in the slightest degree warmer than a piece of ice which has not been exposed to the heat of the warm water. The melting point of ice is therefore a perfectly fixed, definite temperature, above which the ice can never be raised so long as it remains ice, no matter how fast heat is applied to it. All crystalline substances are found to behave exactly like ice in this respect, each substance of this class having its characteristic melting point. The following table gives the melting points of some of the commoner crystalline substances:

Gasoline	(below) – 145° C.	Aluminum	650° C.
Mercury	– 39° C.	Copper	1100° C.
Ice	0° C.	Cast iron	1200° C.
Paraffin	54° C.	Platinum	1775° C.
Sulphur	114° C.	Iridium	1950° C.
Lead	330° C.	Tungsten	3390° C.

We may summarize the experiments upon melting points of crystalline substances in the two following laws:

1. *The temperatures of solidification and fusion are the same.*
2. *The temperature of the melting or solidifying substance remains constant from the moment at which melting or solidification begins until the process is completed.*

197. Fusion of noncrystalline, or amorphous, substances. Let the end of a glass rod be held in a Bunsen flame. Instead of changing suddenly from the solid to the liquid state, it will gradually grow softer and softer until, if the rod is not too thick and the flame is sufficiently hot, a drop of molten glass will finally fall from the end of the rod.

If the temperature of the rod had been measured during this process, it would have been found to be continually rising. This behavior, so completely unlike that of crystalline substances, is characteristic of tar, wax, resin, glue, gutta-percha, alcohol, and in general of all amorphous substances. Such substances cannot be said to have any definite melting

points at all, for they pass through all stages of viscosity both in melting and in solidifying. It is by virtue of this property that glass and other similar substances can be heated to softness and then molded or rolled into any desired shape.

198. Change of volume on solidifying. One has only to reflect that ice floats, or that bottles or crocks of water burst when they freeze, in order to know that water expands upon solidifying. In fact, 1 cubic foot of water becomes 1.09 cubic feet of ice, thus expanding more than one twelfth of its initial volume when it freezes. This may seem strange in view of the fact that the molecules are certainly more closely knit together in the solid than in the liquid state; but the strangeness disappears when we reflect that the molecules of water in freezing group themselves into crystals, and that this operation presumably leaves comparatively large free spaces between different crystals, so that, although groups of individual molecules are more closely joined than before, the total volume occupied by the whole assemblage of molecules is greater.

But the great majority of crystalline substances contract upon solidifying and expand upon liquefying. Water, antimony, bismuth, cast iron, and a few alloys containing antimony or bismuth are the chief exceptions. It is only from substances which expand, or which change in volume very little on solidifying, that sharp castings can be made; for it is clear that contracting substances cannot retain the shape of the mold. It is for this reason that gold and silver coins must be stamped rather than cast. Any metal from which type is to be cast must be one which expands upon solidifying, for it need scarcely be said that perfectly sharp outlines are indispensable to good type. Ordinary type metal is an alloy of lead, antimony, and copper, which fulfills these requirements.

199. Effect of the expansion of water in freezing. If water were not unlike most substances in that it expands on freezing, many, if not all, of the forms of life which now exist on

the earth would be impossible; for in winter the ice would sink in ponds and lakes as fast as it froze, and soon our rivers, lakes, and perhaps our oceans also would become solid ice.

The force exerted by the expansion of freezing water is very great. Steel bombs have been burst by filling them with water and exposing them on cold winter nights. One of the chief agents in the disintegration of rocks is the freezing and consequent expansion of water which has percolated into them.

200. Pressure lowers the melting point of substances which expand on solidifying. Since the outside pressure acting on the surface of a body tends to prevent its expansion, we should expect that any increase in the outside pressure would tend to prevent the solidification of substances which expand upon freezing. It ought therefore to require a lower temperature to freeze ice under a pressure of two atmospheres than under a pressure of one. Careful experiments have verified this conclusion and have shown that the melting point of ice is lowered .0075° C. for an increase of one atmosphere in the outside pressure. Although this lowering is so small a quantity, its existence may be shown as follows:

Let two pieces of ice be pressed firmly together beneath the surface of a vessel full of warm water. When taken out they will be found to be frozen together, in spite of the fact that they have been immersed in a medium much warmer than the freezing point of water. The explanation is as follows:

At the points of contact the pressure reduces the freezing point of the ice below 0° C., and hence it melts and gives rise to a thin film of water the temperature of which is slightly below 0° C. When this pressure is released, the film of water at once freezes, for its temperature is below the freezing point corresponding to ordinary atmospheric pressure. The same phenomenon may be even more strikingly illustrated by the following experiment:

Let two weights of from 5 to 10 kg. be hung by a wire over a block of ice as in Fig. 165. In half an hour or less the wire will be found to have cut completely through the block, leaving the ice, however, as solid as at first. The explanation is as follows: Just

below the wire the ice melts because of the pressure; as the wire sinks through the layer of water thus formed, the pressure on the water is relieved and it immediately freezes again above the wire.

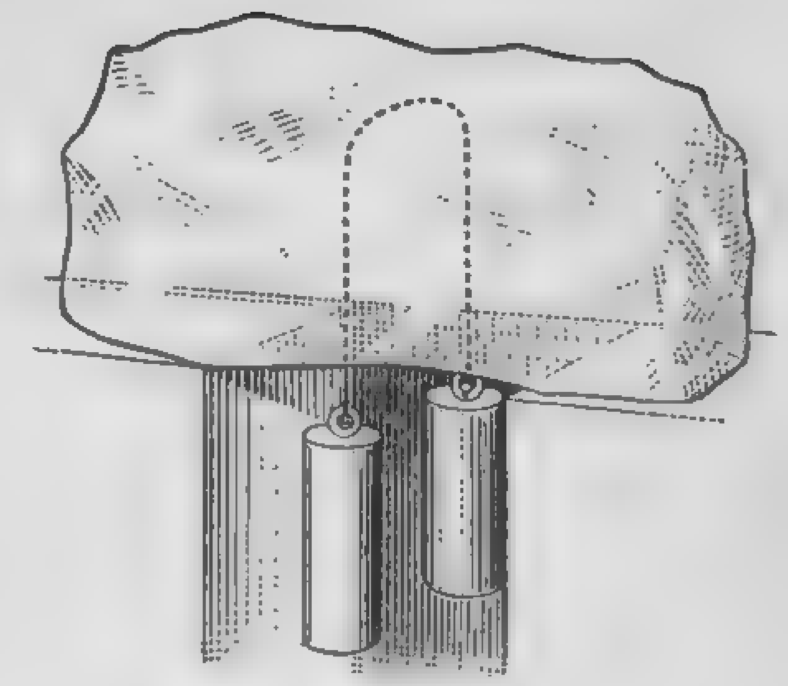


FIG. 165. Regelation

Geologists believe that the continuous flow of glaciers is partly due to the fact that the ice melts at points where the pressures become large, and freezes again when these pressures are relieved. This process of melting under pressure and freezing again as soon as the pressure is relieved is known as *regelation.*

Substances which expand on solidifying have their melting points lowered by pressure, and those which contract on solidifying have their melting points raised by pressure.

SUMMARY. The heat of fusion of any substance is the number of calories of heat energy required to melt one gram of it without producing any change in its temperature.

Eighty calories are absorbed when a gram of ice melts and 80 calories liberated when a gram of water freezes.

Pressure lowers the melting point of substances which expand on solidifying and raises that of substances which contract on solidifying.

QUESTIONS AND PROBLEMS

1. The metal tungsten is used for the filaments of incandescent electric lamps. What is its melting point on the Fahrenheit scale (see table, p. 176)?

2. Explain how the presence of ice keeps the interior of a refrigerator from becoming warm.

3. Which is the more effective as a cooling agent, 100 lb. of ice at 0° C. or 100 lb. of water at the same temperature? Why?

4. What is the meaning of the statement that the heat of fusion of mercury is 2.8?

5. Equal weights of hot water and ice are mixed, and the result is water at 0° C. What was the temperature of the hot water?

6. How many times as much heat is required to melt any piece of ice as to warm the resulting water 1° C.? 1° F.? How many B.T.U., then, are required to melt 1 lb. of ice? How many foot pounds of energy are required to do the work of melting 1 lb. of ice? Where is the energy which disappeared in converting the ice at 0° C. into water at 0° C.?

7. Five pounds of ice melted in 1 hr. in an unopened refrigerator. How many B.T.U. came through the walls of the refrigerator in the hour?

8. A brass calorimeter (specific heat = .1) weighed 100 g. and contained 200 g. of water at 45° C. 100 g. of ice were melted in the hot water with a resulting temperature of 5° C. Calculate the heat of fusion of ice according to the data.

9. A 200-gram iron weight heated to a temperature of 100°C. was placed in a hole bored in a block of ice at temperature 0° C. and allowed to cool to the temperature of the ice. It was found that 27.5 g. of ice melted. Calculate the specific heat of iron.

10. Why will snow pack into a snowball if the snow is melting, but not if it is much below 0° C.?

Evaporation and the Properties of Vapors

201. Evaporation and temperature. If it is true that increase in temperature means increase in the mean velocity of molecular motion, then the number of molecules which chance in a given time to acquire the velocity necessary to carry them into the space above the liquid ought to increase as the temperature increases; that is, evaporation ought to take place more rapidly at high temperatures than at low. Common observation teaches that this is true. Damp clothes become dry under a hot flatiron but not under a cold one; the sidewalk dries more readily in the sun than in the shade; we put wet objects near a hot stove or radiator when we wish them to dry quickly.

202. Evaporation of solids: sublimation. That the molecules of a solid substance are found in a vaporous condition above the surface of the solid, as well as above that of a liquid, is proved by the often-observed fact that ice and

snow evaporate even though they are kept constantly below the freezing point. Thus, wet clothes dry in winter after freezing. An even better proof is the fact that the odor of camphor can be detected many feet away from the camphor crystals. The evaporation of solids may be rendered visible by the following striking experiment:

Let a few crystals of iodine be placed on a watch glass and heated gently with a Bunsen flame. The visible vapor of iodine will appear above the crystals, though none of the liquid is formed.

A great many substances pass at high temperatures from the solid to the gaseous condition without passing through the liquid state. *The vaporization of a solid is called sublimation.*

203. Saturated vapor. If a liquid is placed in an open vessel, there ought to be no limit to the number of molecules which can be lost by evaporation, for as fast as the molecules emerge from the liquid they are carried away by air currents. As a matter of fact, experience teaches that water left in an open dish does waste away until the dish is completely dry.

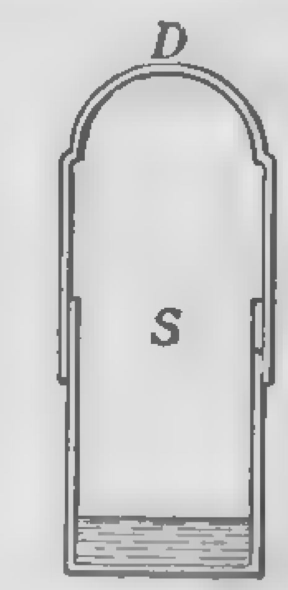


FIG. 166. A saturated vapor

But suppose that the liquid is evaporating into a closed space, such as that shown in Fig. 166. Since the molecules which leave the liquid cannot escape from the space S, it is clear that as time goes on the number of molecules which have passed off from the liquid into this space must continually increase; in other words, the density of the vapor in S must grow greater and greater. But there is a definite limit to the density which the vapor can attain; for as soon as it reaches a certain value, depending on the temperature and on the nature of the liquid, the number of molecules returning per second to the liquid surface will be exactly equal to the number escaping. The vapor is then said to be *saturated.*

If the density of the vapor is lessened temporarily by raising the dome D, more molecules will escape from the

liquid per second than return to it, until the density of the vapor has regained its original value.

If, on the other hand, we lower the dome *D*, the density of the vapor is thereby instantaneously increased, more molecules return to the liquid per second than escape, until by this process the density of the vapor has returned to its saturated value. We learn, then, that *at a given temperature the density of a saturated vapor has a constant value. This value changes with temperature but cannot be affected by changes in volume.*

204. Pressure of a saturated vapor. Just as a gas exerts a pressure against the walls of the containing vessel by the blows of its moving molecules, so also does a confined vapor. But at any given temperature the density of a saturated vapor can have only a definite value; that is, there can be only a definite number of molecules per cubic centimeter. It follows, therefore, that just as at any temperature the saturated vapor can have only one density, so also it can have only one pressure. This pressure is called *the pressure of the saturated vapor* corresponding to the given temperature.

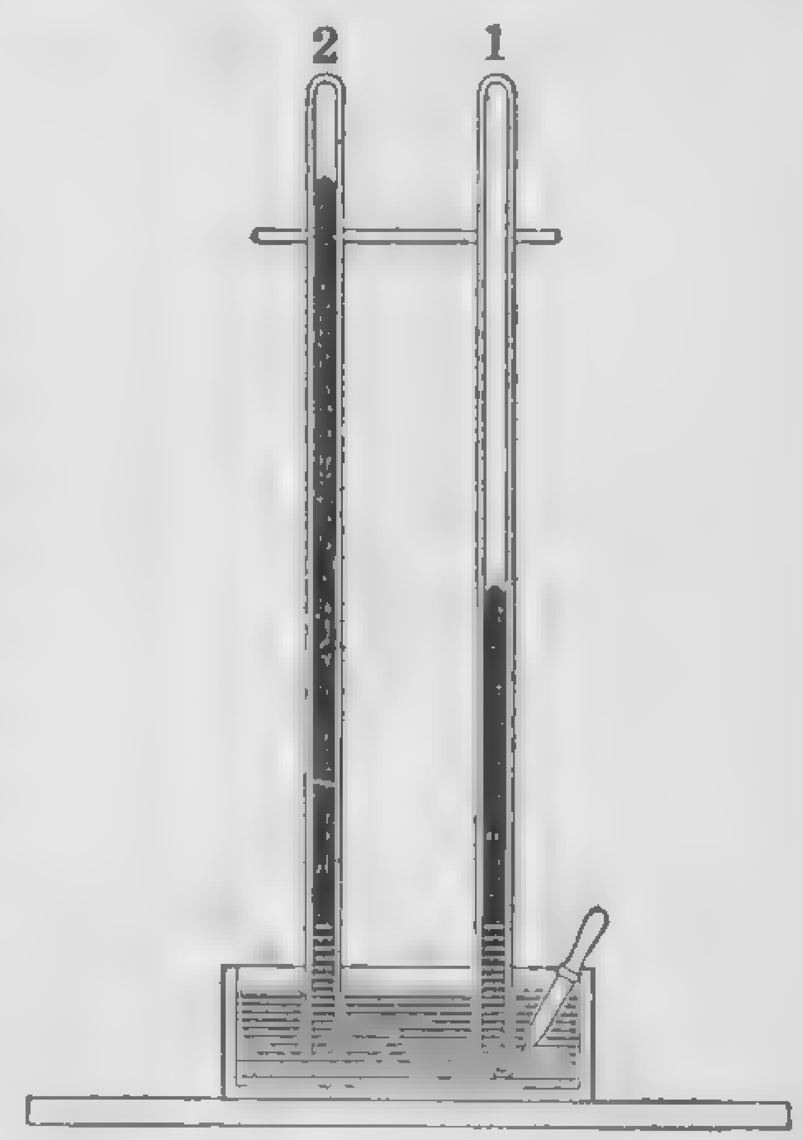


Fig. 167. Vapor pressure of a saturated vapor

Let two Torricelli tubes be set up as in Fig. 167, and with the aid of a curved pipette (Fig. 167) let a drop of ether be introduced into the bottom of tube *1*. This drop will at once rise to the top, and a portion of it will evaporate into the vacuum which exists above the mercury. The pressure of this vapor will push down the mercury column, and the number of centimeters of this depression will be a measure of the pressure of the vapor. It will be observed that the mercury will fall almost instantly to the lowest level which it will ever reach, — a fact which indicates that it takes but a very short time for the condition of saturation to be attained.

The pressure of the saturated ether vapor at the temperature of the room will be found to be as much as 40 centimeters.

Let a Bunsen flame be passed quickly across the tubes of Fig. 167 near the upper level of the mercury. The vapor pressure will increase rapidly in tube *1*, as shown by the fall of the mercury column.

The experiment proves that both the pressure and the density of a saturated vapor increase rapidly with the temperature. This was to have been expected from our theory, for increasing the temperature of the liquid increases the mean velocity of its molecules and hence increases the number which attain each second the velocity necessary for escape. How rapidly the density and pressure of saturated water vapor increase with temperature may be seen from the following table:

TABLE OF CONSTANTS OF SATURATED WATER VAPOR

The table shows the pressure P, in millimeters of mercury, and the density D of aqueous vapor saturated at temperatures t° C.

t	P	D	t	P	D	t	P	D
− 10°	2.2	.0000023	4°	6.1	.0000064	18°	15.3	.0000152
− 9°	2.3	.0000025	5°	6.5	.0000068	19°	16.3	.0000162
− 8°	2.5	.0000027	6°	7.0	.0000073	20°	17.4	.0000172
− 7°	2.7	.0000029	7°	7.5	.0000077	21°	18.5	.0000182
− 6°	2.9	.0000032	8°	8.0	.0000082	22°	19.6	.0000193
− 5°	3.2	.0000034	9°	8.5	.0000087	23°	20.9	.0000204
− 4°	3.4	.0000037	10°	9.1	.0000093	24°	22.2	.0000216
− 3°	3.7	.0000040	11°	9.8	.0000100	25°	23.5	.0000229
− 2°	3.9	.0000042	12°	10.4	.0000106	26°	25.0	.0000242
− 1°	4.2	.0000045	13°	11.1	.0000112	27°	26.5	.0000256
0°	4.6	.0000049	14°	11.9	.0000120	28°	28.1	.0000270
1°	4.9	.0000052	15°	12.7	.0000128	30°	31.5	.0000301
2°	5.3	.0000056	16°	13.5	.0000135	35°	41.8	.0000393
3°	5.7	.0000060	17°	14.4	.0000144	40°	54.9	.0000509

205. The influence of air on evaporation. We observed that when ether was inserted into a Torricelli tube the mercury fell *very suddenly* to its final position, showing that in a vacuum the condition of saturation is reached almost instantly. This

was to have been expected from the great velocities which we found the molecules of gases and vapors to possess.

Let air be introduced into tube *2* (Fig. 167) until the mercury column stands at a height of from 45 to 55 cm. Measure the height of the mercury column. In order to see what effect the presence of air has upon evaporation, let a drop of ether be introduced into the tube. The mercury will not be found to sink instantly to its final level as it did before; but although it will fall rapidly at first, it will continue to fall slowly for several hours. At the end of a day, if the temperature has remained constant, it will show a depression which indicates a vapor pressure of the ether just as great as that existing in a tube which contains no air.

The experiment leads, then, to the rather remarkable conclusion that *just as much liquid will evaporate into a space which is already full of air as into a vacuum.* The air has no effect except to retard greatly the *rate of evaporation.*

206. Explanation of the retarding influence of air on evaporation. This retarding influence of air on evaporation is easily explained by the kinetic theory; for while in a vacuum the molecules which emerge from the surface fly at once to the top of the vessel, when air is present the escaping molecules collide with the air molecules before they have gone any appreciable distance away from the surface (probably less than .00001 centimeter), and only work their way up to the top after an almost infinite number of collisions. Thus, while the space immediately above the liquid may become saturated very quickly, it requires a long time for this condition of saturation to reach the top of the vessel.

SUMMARY. A saturated vapor is a vapor which is in contact with its liquid and is at its maximum possible density for the existing temperature. Any attempt to increase its density further simply produces condensation.

Both the pressure and the density of a saturated vapor depend on temperature alone and both increase rapidly with rising temperature.

The evaporation of a liquid or a solid is retarded by the presence of gases about its surface, but the final density and pressure of its vapor are independent of the presence of these gases.

QUESTIONS AND PROBLEMS

1. Account for the evaporation of naphthaline moth balls at ordinary room temperatures.

2. If the inside of a barometer tube is wet when it is filled with mercury, will the height of the mercury be the same as in a dry tube?

3. How many grams of water will evaporate at 20° C. into a closed room 18 × 20 × 4 m.? (See table, p. 183.)

4. At a temperature of 15° C. what will be the error in the barometric height indicated by a barometer that contains moisture?

5. At 20° C. how great was the error in reading due to the presence of water vapor in Otto von Guericke's barometer?

HYGROMETRY, OR THE STUDY OF MOISTURE CONDITIONS IN THE ATMOSPHERE *

207. Condensation of water vapor from the air. Were it not for the retarding influence of air upon evaporation we should be obliged to live in an atmosphere which would be always completely saturated with water vapor, for the evaporation from oceans, lakes, and rivers would almost instantly saturate all the regions of the earth. This condition — one in which moist clothes would never dry, and in which all objects would be perpetually soaked in moisture — would be exceedingly uncomfortable if not altogether unendurable.

But on account of the slowness with which, as the last experiment showed, evaporation into air takes place, the water vapor which always exists in the atmosphere is usually far from saturated, even in the immediate neighborhood of lakes and rivers. Since, however, the amount of vapor which is necessary to produce saturation rapidly decreases with a fall in temperature, if the temperature decreases continually in some unsaturated locality it is clear that a point must soon be reached at which the amount of vapor already existing in a

* It is recommended that this subject be preceded by a laboratory determination of dew point, humidity, etc. See, for example, Experiments 27 and 28 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

cubic centimeter of the atmosphere is the amount corresponding to saturation. Then, if the temperature still continues to fall, the vapor must begin to condense. Whether it condenses as dew or cloud or fog or rain will depend upon how and where the cooling takes place.

208. The formation of dew and frost. If the cooling is due to the natural radiation of heat from the earth at night after the sun's warmth is withdrawn, the atmosphere itself does not fall in temperature nearly so rapidly as do solid objects on the earth, such as blades of grass, trees, stones, etc. The layers of air which come into immediate contact with these cooled bodies are themselves cooled, and as they thus reach a temperature at which the amount of moisture which they already contain is in a saturated condition, they begin to deposit this moisture, in the form of dew or frost, upon the cold objects. The drops of moisture which collect on an ice pitcher in summer illustrate perfectly the formation of dew. If condensation takes place upon a surface colder than the freezing temperature, *frost* is formed, as is observed, for instance, on grass and on window panes.

209. The formation of fog. If the cooling at night is so great as not only to bring the grass and trees below the temperature at which the vapor in the air in contact with them is in a state of saturation, but also to lower the whole body of air near the earth below this temperature, then the condensation takes place not only on the solid objects but also on dust particles suspended in the atmosphere. This constitutes a fog.

210. The formation of clouds, rain, sleet, hail, and snow. When a warm moist current of air near the surface of the earth rises high into a region of less pressure, *it undergoes a marked lowering in temperature on account of its expansion* (see § 184, last lines). If the resultant temperature due to the expansion is below that at which the amount of moisture already in the air is sufficient to produce saturation, this excessive moisture immediately condenses about floating dust particles and forms a *cloud*. If the cooling is sufficient

to free a considerable amount of moisture, the drops become large and fall as *rain*. If this falling rain freezes before it reaches the ground, it is called *sleet*. If the temperature at which condensation begins is below freezing, the condensing moisture forms into *snowflakes*. When the violent air currents which accompany thunderstorms carry the condensed moisture up and down several times through alternate regions of snow and rain, *hailstones* are formed.

211. The dew point. *The temperature to which the atmosphere must be cooled in order that condensation of the water vapor within it may begin is called the dew point.* This temperature may be found by partly filling with water a brightly polished vessel of 200 or 300 cubic centimeters capacity and dropping into it little pieces of ice, stirring thoroughly at the same time with a thermometer. The dew point is the temperature indicated by the thermometer at the instant a film of moisture appears upon the polished surface. In winter the dew point is usually below freezing, and it will therefore be necessary to add salt to the ice and water in order to make the film appear. The experiment may be performed equally well by bubbling a current of air through ether contained in a polished tube (Fig. 168).

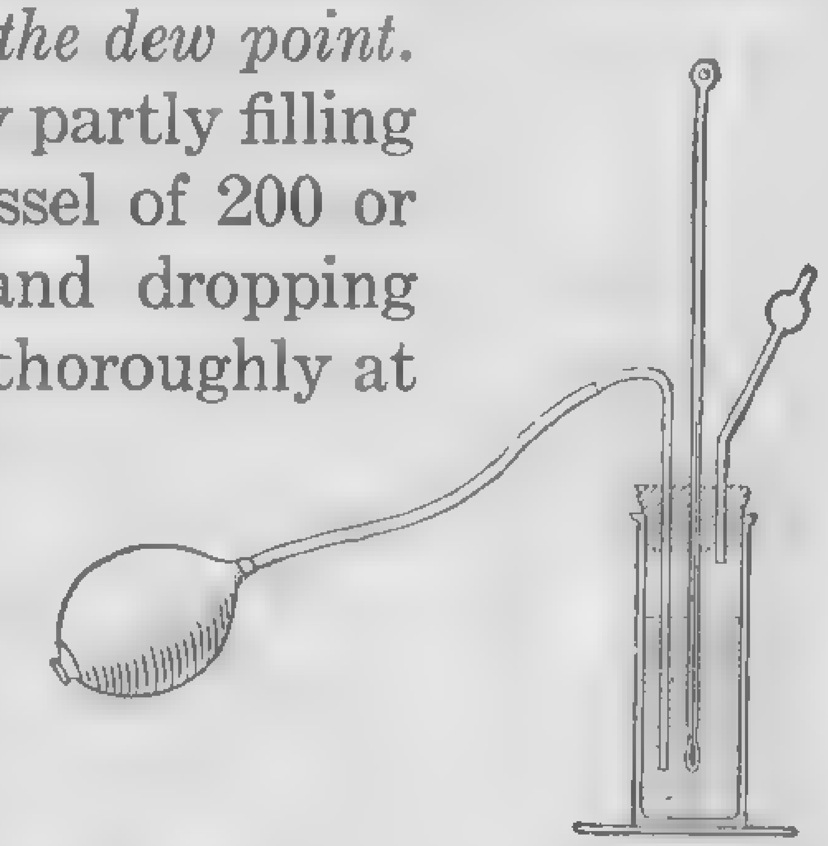


FIG. 168. Apparatus for determining dew point

212. Humidity of the atmosphere. From the dew point and table given in § 204, p. 183, we can easily find what is commonly known as the *relative humidity* or the *degree of saturation* of the atmosphere. *Relative humidity is defined as the ratio between the amount of moisture per cubic centimeter actually present in the air and the amount which would be present if the air were completely saturated.* This is precisely the same as the ratio between the pressure which the water vapor present in the air exerts and the pressure which it would exert if it were present in sufficient quantity to be in the saturated

condition. An example will make clear the method of finding the relative humidity.

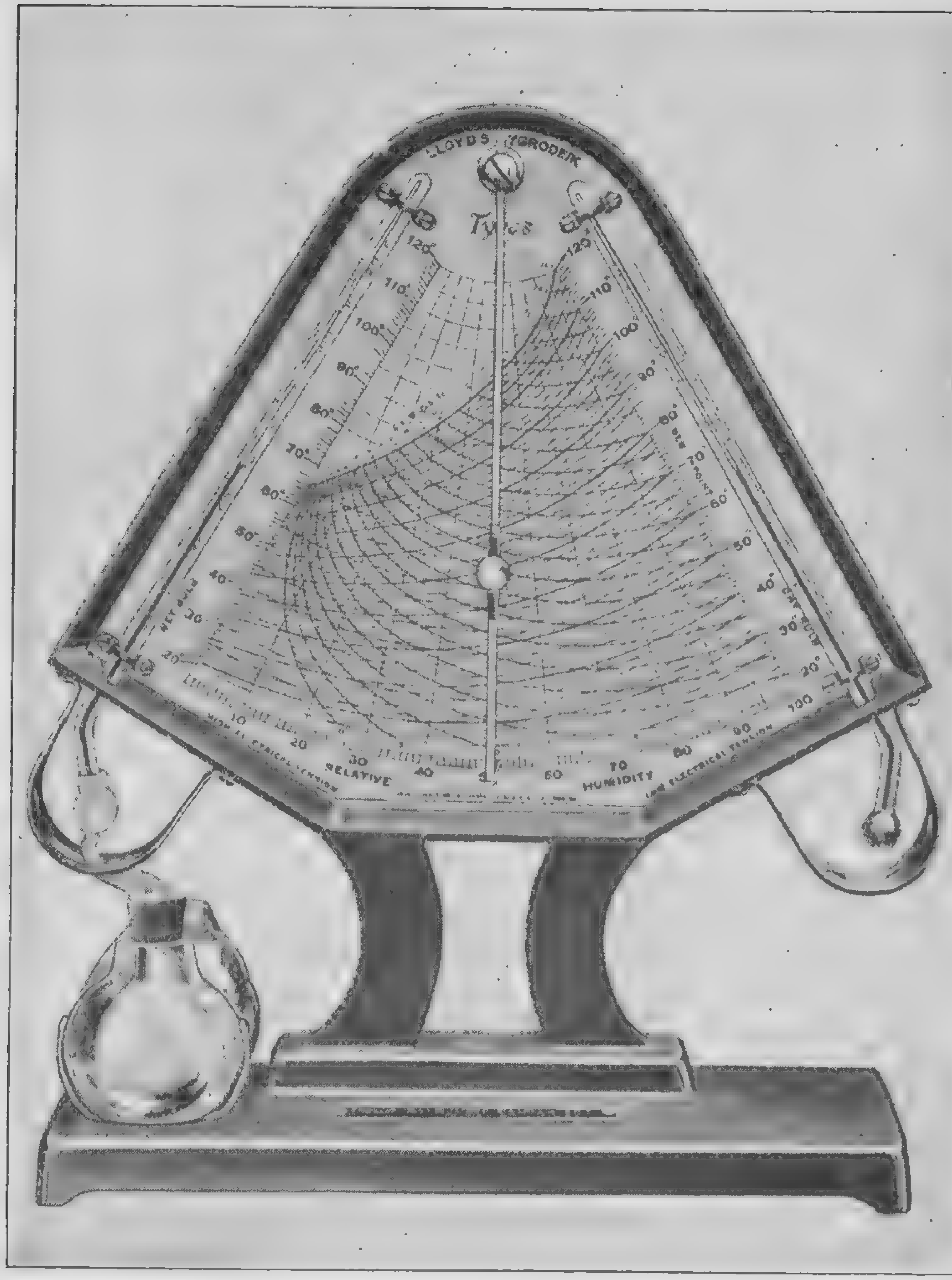
Suppose that the dew point were found to be 15° C. on a day on which the temperature of the room was 25° C. The amount of moisture actually present in the air then saturates it at 15° C. We see from the P column in the table that the pressure of saturated vapor at 15° C. is 12.7 millimeters. This is, then, the pressure exerted by the vapor in the air at the time of our experiment. Running down the table, we see that the amount of moisture required to produce saturation at the temperature of the room, that is, at 25°, would exert a pressure of 23.5 millimeters. Hence at the time of the experiment the air contains 12.7/23.5, or .54, as much water vapor as it might hold. We say, therefore, that the air is 54 per cent saturated, or that the relative humidity is 54 per cent.

213. Practical value of humidity determinations. From humidity determinations it is possible to get much information regarding the likelihood of rain or frost. Such observations are continually made for this purpose at all meteorological stations. They are also made in greenhouses, to see that the air does not become too dry for the health of the plants, and in hospitals and public buildings and even in private dwellings, in order to insure the maintenance of hygienic living conditions. For the most healthful conditions the relative humidity should be kept at from 50 per cent to 60 per cent.

Low relative humidity in the home causes discomfort and colds, and leads to waste of fuel estimated at from 10 per cent to 25 per cent. The average home heated to 72° F. by steam or hot water is estimated by health authorities to have a relative humidity of 30 per cent, and even as little as 25 per cent with hot-air heating. This is less than the average humidity of extensive desert regions. Higher humidity in the home would diminish the cooling effect due to rapid evaporation of the perspiration from the body, and would make us feel comfortable if a lower temperature were maintained (see § 214).

JOSEPH HENRY (1797–1878)

Born in Albany, New York; taught physics and mathematics in Albany Academy and Princeton College; invented the electromagnet (1828), discovered the oscillatory nature of the electric spark (1842) by magnetizing needles in the manner described on page 263, and made the first experiments in self-induction (1832); was the first secretary of the Smithsonian Institute and the organizer of the Climatological Service, a branch of the Weather Bureau which collects the weather observations of nearly five thousand unpaid coöperative observers located in all sections of the United States



THE HYGRODEIK

214. Cooling effect of evaporation. Let three shallow dishes be partly filled, the first with water, the second with alcohol, and the third with ether, the bottles from which these liquids are obtained having stood in the room long enough to acquire its temperature. Let three students carefully read as many thermometers, first before their bulbs have been immersed in the respective liquids and then after. In every case the temperature of the liquid in the shallow vessel will be found to be somewhat lower than the temperature of the air, the difference being greatest in the case of ether and least in the case of water.

It appears from this experiment that an evaporating liquid assumes a temperature somewhat lower than its surroundings and that the substances which evaporate the most readily assume the lowest temperatures.

In dry, hot climates where ice is not readily obtained drinking water is frequently kept in canvas bags or unglazed earthenware. The slow evaporation of the water from the outside of the porous container keeps the water within quite cool.

Another way of establishing the same fact is to place a few drops of each of the above liquids in succession on the bulb of the arrangement shown in Fig. 148 and observe the rise of water in the stem; or, more simply still, to place a few drops of each liquid on the back of the hand and notice that the order in which they evaporate — namely, ether, alcohol, water — is the order of greatest cooling.

In twenty-four hours a healthy person perspires from a pint to a quart, while one who exercises violently may perspire a gallon in that time.

215. Explanation of the cooling effect of evaporation. The kinetic theory furnishes a simple explanation of the cooling effect of evaporation. We saw that, in accordance with this theory, evaporation means an escape from the surface of those molecules which have acquired velocities considerably above the average. But such a continual loss of the most rapidly moving molecules involves, of course, a continual diminution of the average velocity of the molecules left behind, and this means a decrease in the temperature of the liquid.

Again, we should expect the amount of cooling to be proportional to the rate at which the liquid is losing molecules. Hence, of the three liquids studied, ether should cool most rapidly, since it evaporates most rapidly.

216. Freezing by evaporation. In § 205 it was shown that a liquid will evaporate much more quickly into a vacuum than into a space containing air. Hence, if we place a liquid under the receiver of an air pump and exhaust rapidly, we ought to expect a much greater fall in temperature than when the liquid evaporates into air. This conclusion may be strikingly verified as follows:

Let a thin watch glass be filled with ether and placed upon a drop of cold water, preferably ice water, which rests upon a thin glass plate. Let the whole arrangement be placed underneath the receiver of an air pump and the air rapidly exhausted. After a few minutes of pumping the watch glass will be found frozen to the plate.

It was by evaporating liquid helium in this way that Professor Kamerlingh Onnes of Leyden, in 1923, attained the lowest temperature that had ever been reached, namely, −272.18° C. (−457.9° F.), less than 1° C. above absolute zero.

217. Effect of air currents upon evaporation. Let four thermometer bulbs, the first of which is dry, the second wet with water, the third with alcohol, and the fourth with ether, be rapidly fanned and their respective temperatures observed. The results will show that in all of the wet thermometers the fanning will considerably augment the cooling, but the dry thermometer will be wholly unaffected.

The reason why fanning thus facilitates evaporation, and therefore cooling, is that it removes the saturated layers of vapor which are in immediate contact with the liquid and replaces them by unsaturated layers into which new evaporation may at once take place. From the behavior of the dry-bulb thermometer, however, it will be seen that fanning produces cooling only when it can thus hasten evaporation. A dry body at the temperature of the room is not cooled in the slightest degree by blowing a current of air across it.

218. The wet-and-dry-bulb hygrometer. In the wet-and-dry-bulb hygrometer (Fig. 169) the principle of cooling by evaporation finds a very useful application. This instrument consists of two thermometers, the bulb of one of which is dry, and that of the other is kept continually moist by a wick dipping into a vessel of water. Unless the air is saturated the wet bulb indicates a lower temperature than the dry one, for the reason that evaporation is continually taking place from its surface. How much lower will depend on how rapidly the evaporation proceeds, and this in turn will depend upon the relative humidity of the atmosphere. Thus, in a completely saturated atmosphere no evaporation whatever takes place at the wet bulb, and it consequently indicates the same temperature as the dry one. By comparing the indications of this instrument with those of the dew-point hygrometer (Fig. 168) tables have been constructed which enable one to determine at once from the readings of the two thermometers both the relative humidity and the dew point.* On account of their convenience instruments of this sort are used almost exclusively in practical work. They are not very reliable unless the air is made to circulate about the wet bulb before the reading is taken. In scientific work this is always done. Opposite page 189 is shown a wet-and-dry-bulb hygrometer the scale of which obviates the use of all tables; the relative humidity, dew point, and other information being obtained directly from the intersecting curved lines. The form of instrument used by the United States Weather Bureau is shown in Fig. 169.

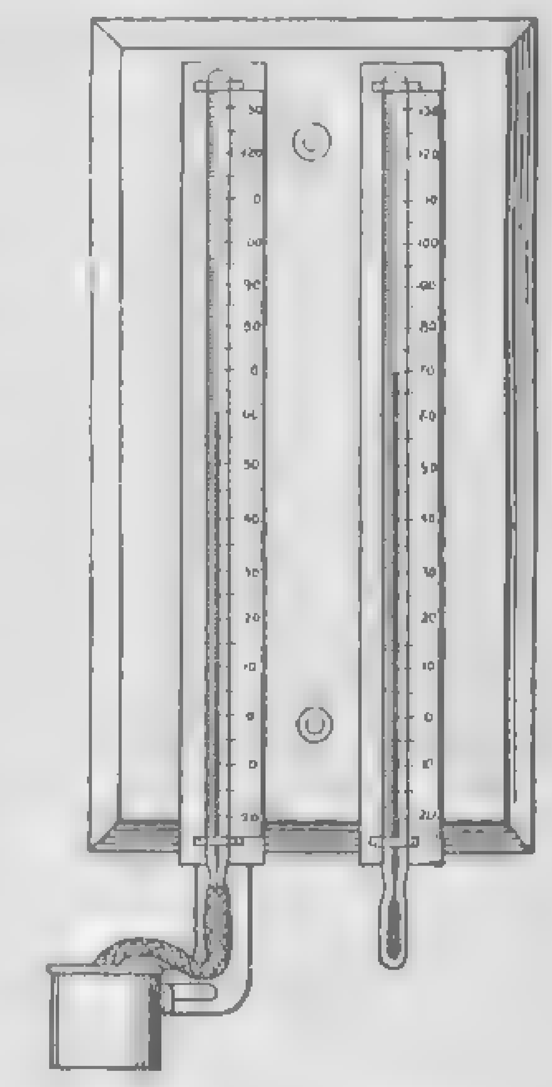


FIG. 169. Wet-and-dry-bulb hygrometer

* Psychrometric tables may be obtained from the United States Weather Bureau, Washington, D.C.

219. Effect of increased surface upon evaporation. Let a small test tube containing a few drops of water be dipped into a larger tube or a small glass containing ether, as in Fig. 170, and let a current of air be forced rapidly through the ether with an aspirator in the manner shown. The water within the tube will be frozen in a few minutes, if the aspirator is operated vigorously. The experiment works most successfully if the walls of the test tube are quite thin and the walls of the outer vessel fairly thick. Why?

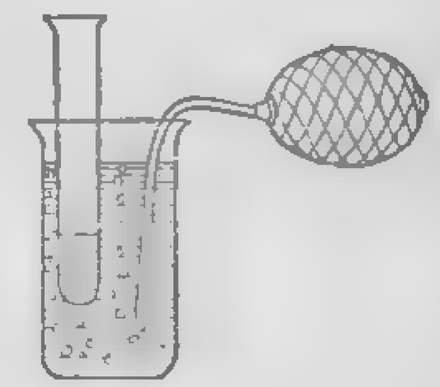


FIG. 170. Freezing water by the evaporation of ether

The effect of passing bubbles through the ether is simply to increase enormously the surface, from which evaporation takes place, for the ether molecules which could before escape only at the upper surface can now escape into the air bubbles as well.

220. Factors affecting evaporation. The above results may be summarized as follows: The rate of evaporation depends (1) on the nature of the evaporating liquid; (2) on the temperature of the evaporating liquid; (3) on the degree of saturation of the space into which the evaporation takes place; (4) on the density of the air or other gas above the evaporating surface; (5) on the rapidity of the circulation of the air above the evaporating surface; (6) on the extent of the exposed surface of the liquid.

SUMMARY. Cooling an unsaturated vapor sufficiently will bring it to a state of saturation; condensation results from further cooling. Depending upon the external conditions, this condensation may appear as dew, frost, fog, clouds, sleet, snow, rain, or hail.

The dew point is the temperature to which the atmosphere must be cooled in order that condensation of the water vapor within it may begin.

Relative humidity is the ratio between the amount of moisture per cubic centimeter actually present in the air and the amount which would be present if the air were completely saturated.

The cooling effect of evaporation is due to the evaporation of the more lively molecules and the consequent diminution in the average kinetic energy of the remaining molecules.

QUESTIONS AND PROBLEMS

1. At the spout of a boiling teakettle you see first a clear space and then a white cloud. Explain.

2. Why do one's spectacle lenses become coated with mist when one enters a warm house on a cold winter day?

3. Dew will not usually collect on a pitcher of ice water standing in a warm room on a cold winter day. Explain.

4. Explain the formation of frost on the grass.

5. Explain under what conditions frost will form on the inside surface of a window of a house and not on the outside surface.

6. The dew point in a room was found to be 8° C. What was the relative humidity if the temperature of the air was 10° C.? 20° C.? 30° C.? (Consult table, p. 183.)

7. Describe any personal experience which shows that evaporation is a cooling process.

8. If a glass beaker and a porous earthenware vessel are filled with equal amounts of water at the same temperature, in the course of a few minutes a noticeable difference of temperature will exist between the two vessels. Which will be the cooler, and why? Will the difference in temperature between the two vessels be greater in a dry or in a moist atmosphere?

9. Why is the heat so oppressive on a very damp day in summer?

10. State what factors affecting evaporation are illustrated by the following: (1) a wet handkerchief dries faster if spread out; (2) clothes dry best on a windy day; (3) clothes do not dry rapidly on a cold day; (4) clothes dry slowly on moist days. Explain each fact.

BOILING*

221. Heat of vaporization defined. The experiments performed in Chapter IV, "Molecular Motions," led us to the conclusion that, at the free surface of any liquid, molecules

* It is recommended that this subject be accompanied by a laboratory determination of the boiling point of alcohol by the direct method and by the vapor-pressure method, and that it be followed by an experiment upon the fixed points of a thermometer, the change of boiling point with pressure, and heat of condensation. See, for example, Experiments 18, 19, and 29 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

frequently acquire velocities sufficiently high to enable them to lift themselves beyond the range of attraction of the molecules of the liquid and to pass off as free gaseous molecules into the space above. They taught us, further, that since it is only such molecules as have unusually high velocities which are able thus to escape, the *average kinetic energy* of the molecules left behind is continually diminished by this loss from the liquid of the most rapidly moving molecules, and consequently the temperature of an evaporating liquid constantly falls until the rate at which it is losing heat is equal to the rate at which it receives heat from outside sources. Evaporation, therefore, always takes place at the expense of the heat energy of the liquid. *The number of calories of heat which disappear in the formation of one gram of vapor is called the heat of vaporization of the liquid.*

222. Heat due to condensation. When molecules pass off from the surface of a liquid, they rise against the downward forces exerted upon them by the liquid, and in so doing exchange a part of their kinetic energy for the potential energy of separated molecules in precisely the same way in which a ball thrown upward from the earth exchanges its kinetic energy in rising for the potential energy which is represented by the separation of the ball from the earth. Similarly, just as when the ball falls back it regains in the descent all the kinetic energy lost in the ascent; so when the molecules of the vapor reënter the liquid they must regain all of the kinetic energy which they lost when they passed out of the liquid. We may expect, therefore, that *every gram of steam which condenses will generate in this process the same number of calories as was required to vaporize it.* This is the principle of the steam heating of buildings, by which the heat energy that disappears in converting the water in the boilers into steam is generated again when the steam condenses to water within the radiators.

223. Measurement of heat of vaporization. To find accurately the number of calories expended in the vaporization, or released in

the condensation, of a gram of water at 100° C., we pass steam rapidly for two or three minutes, from an arrangement like that shown in Fig. 171, into a vessel containing, say, 500 g. of water. We observe the initial and final temperatures and the initial and final weights of the water. If, for example, the gain in weight of the water is 16.4 g., we know that 16.4 g. of steam have been condensed. If the rise in temperature of the water is from 10° C. to 30° C., we know that $500 \times (30 - 10) = 10{,}000$ calories of heat have entered the water. If x represents the number of calories given up by 1 g. of steam in condensing, then the total heat imparted to the water by the condensation of the steam is $16.4\,x$ calories. This condensed steam is at first water at 100° C., which is then cooled to 30° C. In this cooling process it gives up $16.4 \times (100 - 30) = 1148$ calories. Therefore, equating the heat gained by the water to the heat lost by the steam, we have

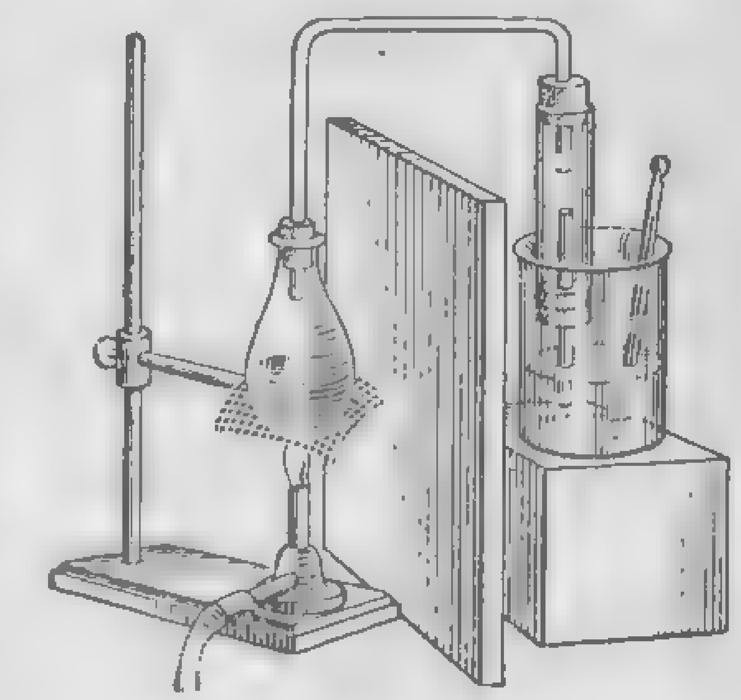


FIG. 171. Heat of vaporization of water

$$10{,}000 = 16.4\,x + 1148, \text{ or } x = 539 \text{ at } 100^\circ \text{ C.}$$

This is the method usually employed for finding the heat of vaporization. The now accepted value of this constant is 539 calories per gram or 970 B.T.U. per pound.

224. Boiling temperature defined. If a liquid is heated by means of a flame, it will be found that there is a certain temperature above which it cannot be raised, no matter how rapidly the heat is applied. This is the temperature which exists when bubbles of vapor form at the bottom of the vessel and rise to the surface, growing larger as they rise. This temperature is commonly called the *boiling temperature.*

But a second and more exact definition of the boiling point may be given. It is clear that a bubble of vapor can exist within the liquid only when the pressure exerted by the vapor within the bubble is at least equal to the atmospheric pressure pushing down on the surface of the liquid; for if the pressure within the bubble were less than the outside pressure,

the bubble would immediately collapse. Therefore *the boiling point is the temperature at which the pressure of the saturated vapor first becomes equal to the pressure existing outside.*

The following table gives the boiling points of some common substances:

Air	− 180° C.	Brine (saturated)	108° C.
Ammonia	− 33° C.	Turpentine	160° C.
Ether	35° C.	Mercury	357° C.
Alcohol (grain)	78° C.	Lead	1800° C.
Gasoline	75 – 80° C.	Iron	2450° C.

225. Variation of the boiling point with pressure. Since the boiling point has been defined as the temperature at which the pressure of the saturated vapor is equal to the outside pressure, and since the pressure of a saturated vapor varies rapidly with the temperature, it follows that *the boiling point must vary as the outside pressure varies.*

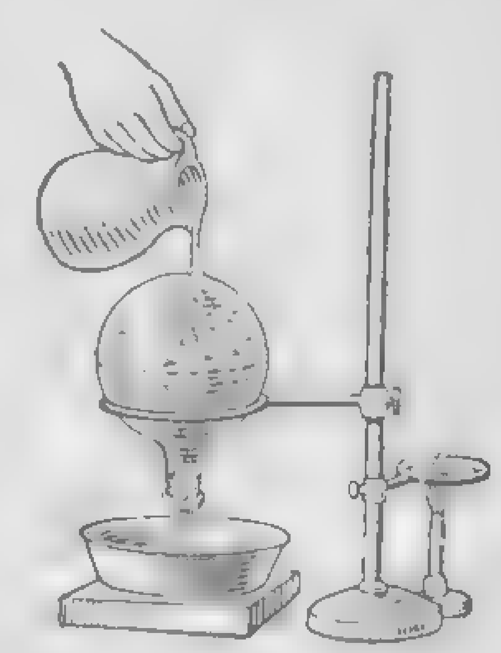


Fig. 172. Lowering the boiling point by diminishing the pressure

Thus let a round-bottomed flask be half filled with water and boiled. After the boiling has continued for a few minutes, so that the steam has driven out most of the air from the flask, let a rubber stopper be inserted and the flask removed from the flame and inverted as shown in Fig. 172. The temperature will fall rapidly below the boiling point; but if cold water is poured over the flask, the water will again begin to boil vigorously, for the cold water, by condensing the steam, lowers the pressure within the flask, and thus enables the water to boil at a temperature lower than 100° C. The boiling will cease, however, as soon as enough vapor is formed to restore the pressure. The operation may be repeated many times without reheating.

At the city of Quito, Ecuador, water boils at 90° C.; on the top of Mt. Blanc it boils at 84° C.; and on Pikes Peak, at 89° C. On the other hand, in the boiler of a locomotive on which the gauge records a pressure of 250 pounds, as is frequently the case, the boiling point of the water is 208° C. (406° F.).

Closed boilers provided with safety valves (see *C*, Fig. 173) and known as *digesters* or *pressure cookers* are used for more rapid cooking in mountainous regions. Indeed, a temperature only a few degrees above 100° C. causes starch grains to burst open much more rapidly than does a temperature of 100° C. Large digesters are used in extracting gelatin from bones and in reclaiming valuable fatty substances at garbage plants. In the cold-pack method of preserving fruits and vegetables the final sterilizing is done by placing the jars or cans in closed boilers known as *steam-pressure canners.**

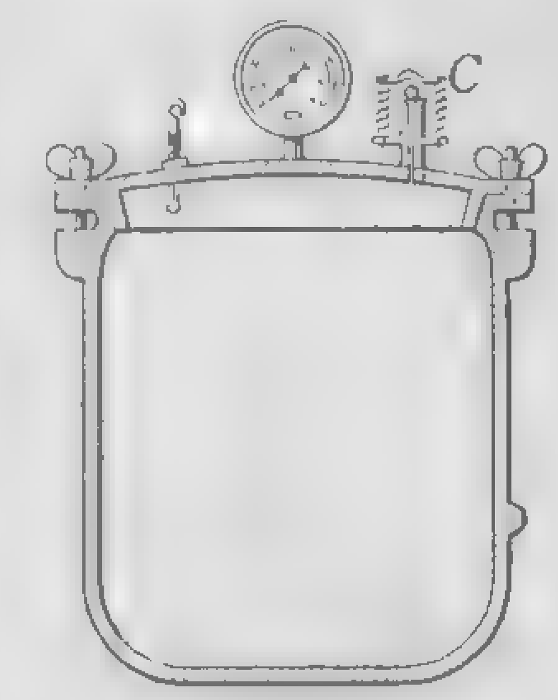


Fig. 173. A closed boiler for family use

226. Evaporation and boiling. The only essential difference between evaporation and boiling is that the former consists in the passage of molecules into the vaporous condition *from the free surface only,* whereas the latter consists in the passage of the molecules into the vaporous condition both at the free surface and at the surface of bubbles which exist within the body of the liquid. The only reason why vaporization takes place so much more rapidly at the boiling temperature than just below it is that the evaporating *surface* is enormously increased as soon as the bubbles form. The reason why the temperature cannot be raised above the boiling point is that the surface always increases, on account of the bubbles, to just such an extent that the loss of heat because of evaporation is exactly equal to the heat received from the fire.

227. Manufactured ice. Fig. 174 shows the essential parts of a modern industrial ice plant. A compressor run by an engine forces gaseous ammonia under a pressure of 155 pounds into the condenser coils shown on the right, and there liquefies it. The heat of condensation of the ammonia is carried off by the running

* *Farmers' Bulletin No. 839,* on steam-pressure canning, may be obtained from the United States Department of Agriculture, Washington, D.C.

water which constantly circulates about the condenser coils. From the condenser the liquid ammonia is allowed to pass very slowly through the regulating valve *V* into the coils of the evaporator, from which the evaporated ammonia is pumped out so rapidly that the pressure within the coils does not rise above 34 pounds. The compressor acts as an exhaust pump on one side and as a compression pump on the other. The rapid evaporation of the liquid ammonia within the evaporator cools these coils to a temperature of about 5° F. The brine with which these coils are

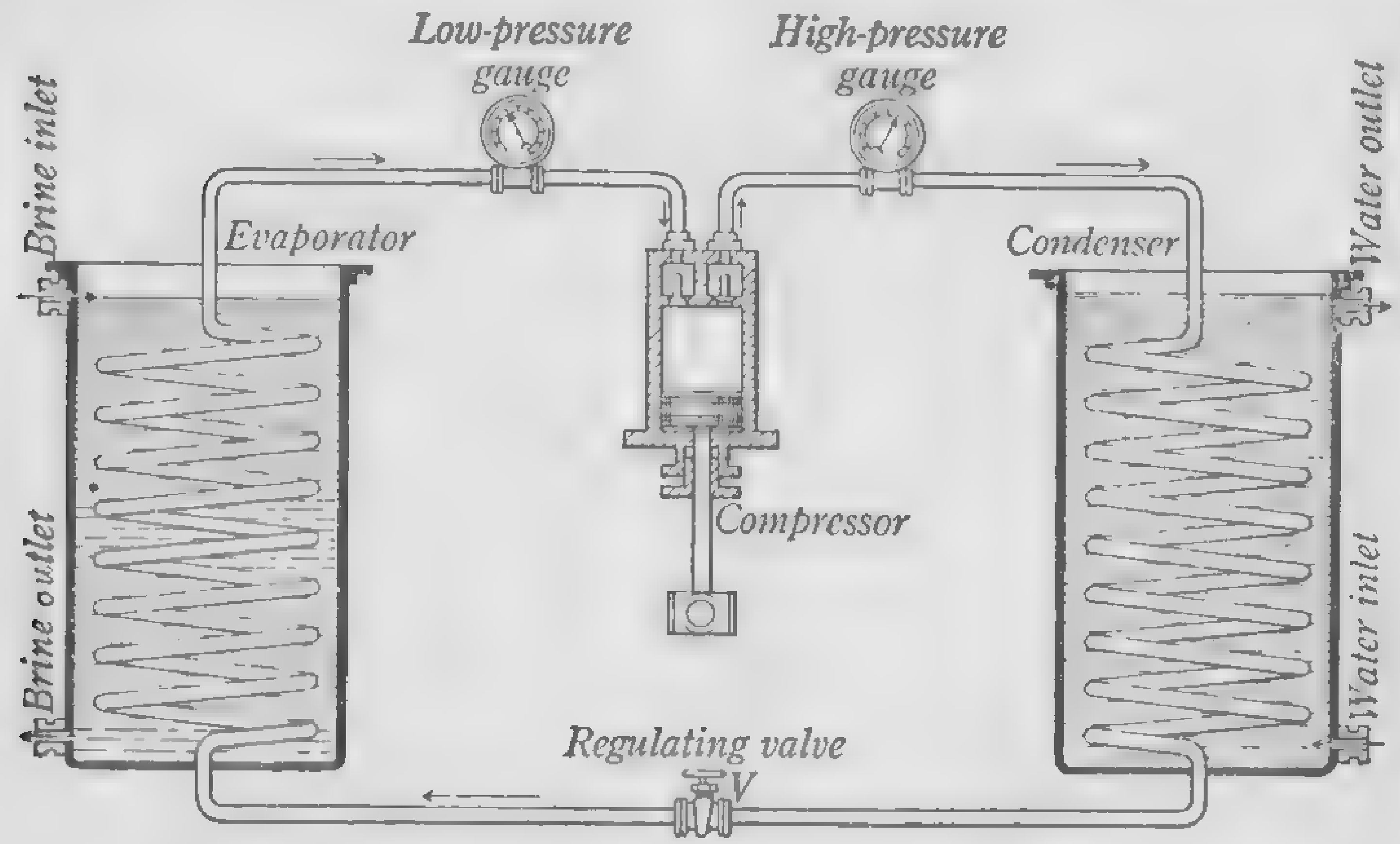


FIG. 174. Compression system of ice manufacture

surrounded has its temperature thus reduced to about 16° or 18° F. This brine is made to circulate about the cans containing the water to be frozen. The heat of vaporization of ammonia at 5° F. is 314 calories.

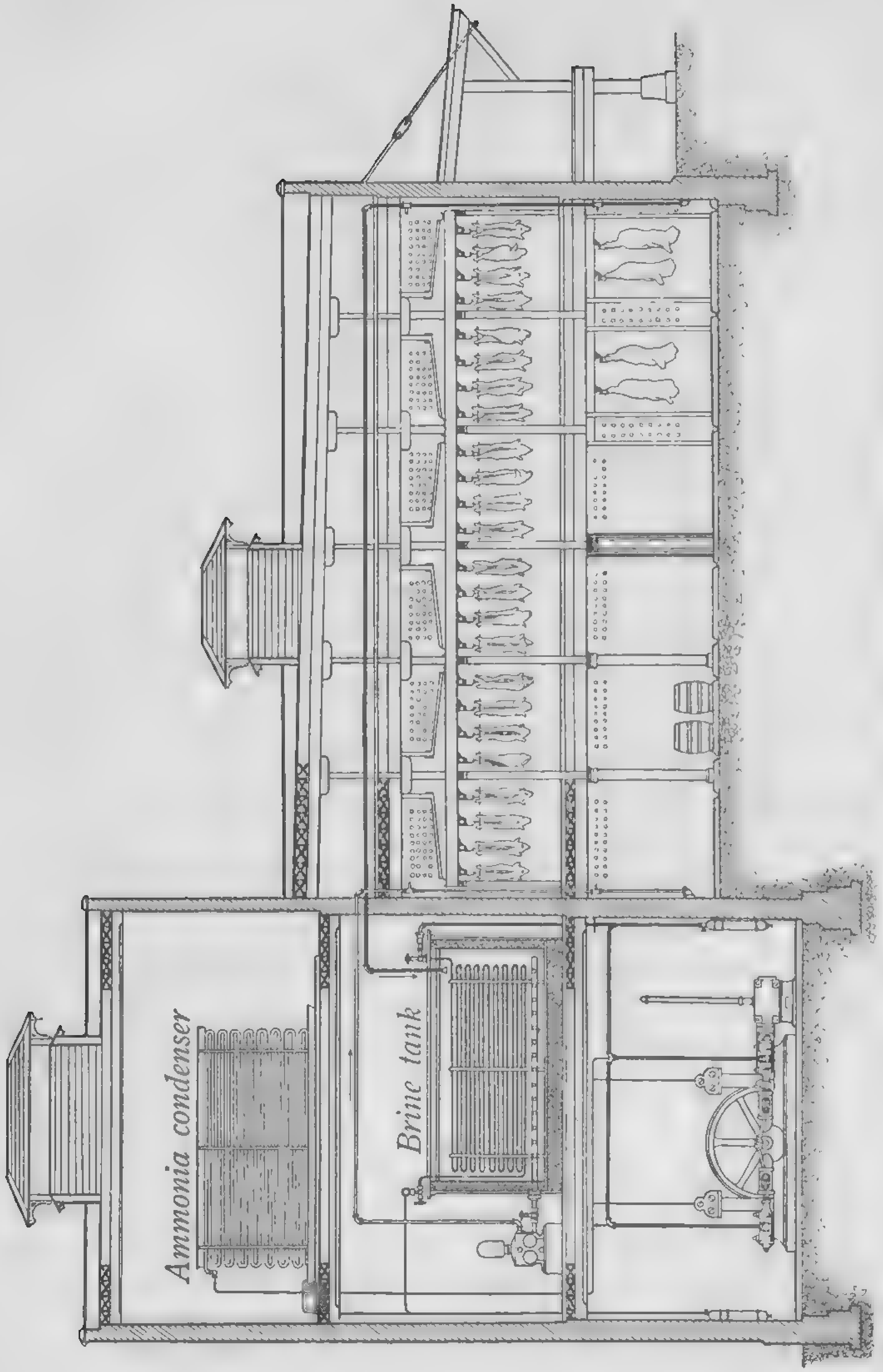
Large indoor skating rinks are made by laying thousands of feet of iron pipe horizontally, covering the system with water to be frozen, and then circulating through it intensely cold brine.

228. Cold storage. The artificial cooling of factories and cold storage rooms is accomplished in a manner exactly similar to that employed in the manufacture of ice. The brine is cooled precisely as described above, and is then pumped through coils placed in the rooms to be cooled. Opposite page 199 is a sketch of such a refrigerating plant in a packing house. The ammonia is liquefied in the *condenser* and evaporated in the coils of the *brine tank*. In some

HOUSEHOLD REFRIGERATION BY THE USE OF LIQUID SO_2

The compressing pump *P* run by the electric motor *E* liquefies by pressure the gas SO_2 in the compressor coils C, the heat of condensation being partially removed by the fan *F*. The liquid SO_2 escaping through the expansion valve *V* into the evaporating coils immersed in the brine tank *B* rapidly evaporates under the reduced pressures in these coils and maintains the whole tank below the freezing temperature. The thermostat *T* opens and closes the circuit to the electric motor as needed to maintain constant temperature. The brine tank takes the place of the cake of ice in the old refrigerator. In some systems the brine tank is absent and the evaporating coils themselves take the place of the ice.

(Courtesy of the Kelvinator Corporation)



PACKING HOUSE WITH BRINE SYSTEM OF REFRIGERATION

systems carbon dioxide is used instead of ammonia, but the principle is in no way altered. Sometimes, too, the brine is dispensed with, and the air of the rooms to be cooled is forced by means of fans directly over the cold coils containing the evaporating ammonia or carbon dioxide. It is in this way that theaters and hotels are cooled. (See "Electric refrigeration," opposite page 198.)

229. Distillation. Let water holding in solution some aniline dye be boiled in *B* (Fig. 175). The vapor of the liquid will pass into the tube *T*, where it will be condensed by the cold water which is kept in continual circulation through the jacket *J*. The condensed water collected in *P* will be seen to be free from all traces of the color of the dissolved aniline.

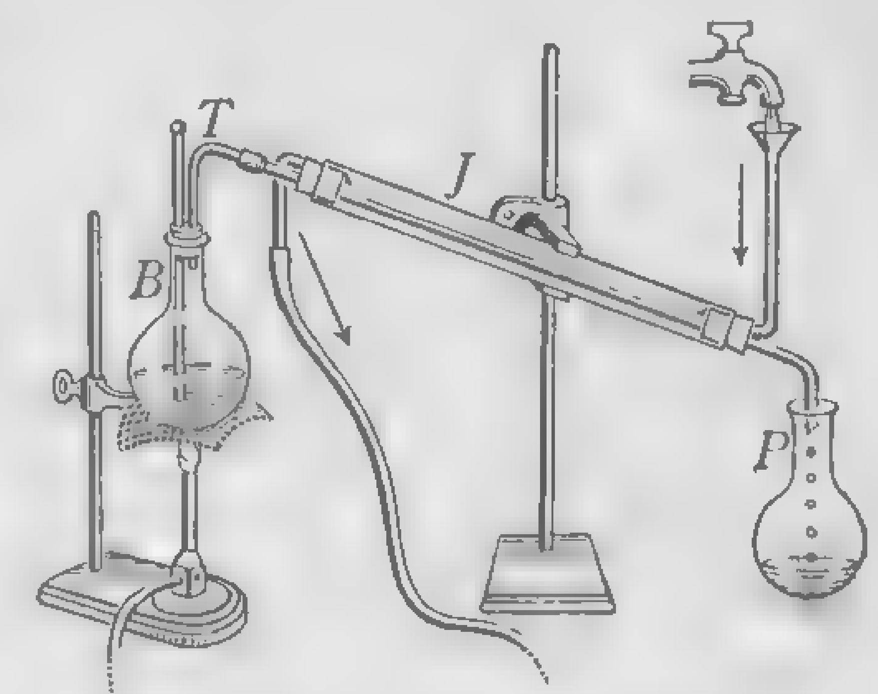


FIG. 175. Distillation

We learn, then, that *when solids are dissolved in liquids, the vapor which rises from the solution contains none of the dissolved substance.* Sometimes it is the pure liquid in *P* which is desired, as in the manufacture of alcohol, and sometimes the solid which remains in *B*, as in the manufacture of sugar. In the white-sugar industry it is necessary that the evaporation take place at a low temperature, so that the sugar may not be scorched. Hence the boiler is kept partially exhausted by means of an air pump, thus enabling the solution to boil at considerably reduced temperatures.

230. Fractional distillation. When both the constituents of a solution are volatile, as in the case of a mixture of alcohol and water, the vapor of both will rise from the liquid. But the one which has the lower boiling point, that is, the higher vapor pressure, will predominate. Hence, if we have in *B* (Fig. 175) a solution consisting of 50 per cent alcohol and 50 per cent water, it is clear that we can obtain in *P*, by evaporating and condensing, a solution containing a much larger percentage of alcohol. By repeating this operation a number of times we can increase the purity of the alcohol.

This process is called *fractional distillation.* The boiling point of the mixture lies between the boiling points of alcohol and water, being higher the greater the percentage of water in the solution.

Gasoline and kerosene are separated from crude oil, and different grades of gasoline are separated from each other by fractional distillation.

231. Cooling by solution. Let a handful of common salt be placed in a small beaker of water at the temperature of the room and stirred with a thermometer. The temperature will fall several degrees. If equal weights of ammonium nitrate and water at 15° C. are mixed, the temperature will fall as low as − 10° C. If the water is nearly at 0° C. when the ammonium nitrate is added, and if the stirring is done with a test tube partly filled with ice-cold water, the water in the tube will be frozen.

These experiments show that the breaking up of the crystals of a solid requires an expenditure of heat energy, as well when this operation is effected by solution as by fusion.

232. Freezing points of solutions. If a solution of one part of common salt to ten of water is placed in a test tube and immersed in a "freezing mixture" of water, ice, and salt, the temperature indicated by a thermometer in the tube will not be zero when ice begins to form, but several degrees below zero. *The ice which does form, however, will be found, like the vapor which rises above the ocean or any other salt solution, to be free from salt,* and it is this fact which furnishes a key to the explanation of why the freezing point of the salt solution is lower than that of pure water. For cooling a substance to its freezing point simply means reducing its temperature, and therefore the mean velocity of its molecules, sufficiently to enable the cohesive forces of the liquid to pull the molecules together into the crystalline form. Since in the freezing of a salt solution the cohesive forces of the water acting to form the ice are obliged to overcome the attractions of the salt molecules as well as the motions of the water molecules, the motions must be rendered less, that is, the temperature must be made lower, than in the case of pure water in order that crystallization may occur. From this reasoning we should expect that the larger the amount of salt in solution the lower would be the freezing point. This is indeed the case. The lowest freezing point obtainable with common salt in water is − 22° C., or − 7.6° F. This is the freezing point of a saturated solution.

233. Freezing mixtures. If snow or ice is placed in a vessel of water, the water melts it, and in so doing its temperature is reduced to the freezing point of pure water. Similarly, if ice is placed in salt water, it melts and reduces the temperature of the salt water to the freezing point of the solution. This may be one, or two, or twenty-two degrees below zero, according to the concentration of the solution. Therefore, whether we put the ice in pure water or in salt water, enough of it always melts to reduce the whole mass to the freezing point of the liquid, and each gram of ice which melts uses up 80 calories of heat. *The efficiency of a mixture of salt and ice in lowering temperature is therefore due simply to the fact that the freezing point of a salt solution is lower than that of pure water.*

The best proportions are three parts of snow or finely shaved ice to one part of common salt. If three parts of calcium chloride are mixed with two parts of snow, a temperature of − 55° C. may be produced. This is low enough to freeze mercury.

Summary. The heat of vaporization of a liquid is the number of calories of heat absorbed in the formation of 1 gram of vapor or liberated in its condensation. For water at 100° C. it is 539 calories.

The boiling temperature of a liquid is the temperature at which bubbles of its vapor form and rise as such through the body of the liquid; or, it is the temperature at which the pressure of the saturated vapor first becomes equal to the pressure on the surface of the liquid.

Distillation is a process of vaporization and condensation by which a liquid is separated from a solid dissolved in it, or by which intermingled liquids having different boiling points are separated.

Cooling by solution of a solid occurs because of the work which has to be done in pulling apart the molecules of the solid crystals. Molecular velocity is lost; that is, heat disappears in doing this work.

The freezing point of salt water is lower than that of fresh water because the attraction of the salt molecules for the water molecules tends to keep the latter from arranging themselves into crystals of pure ice. At a lower temperature (smaller energy of agitation) the cohesive forces get the mastery and form the pure ice.

A mixture of salt and ice becomes cold because, on account of the low freezing point of salt water (temperature of equilibrium between salt water and ice) the ice begins to melt when brought in contact with the salt and the 80 calories per gram necessary for this melting is taken from the mixture.

QUESTIONS AND PROBLEMS

1. After the water in an open vessel first begins to boil, a long time elapses before it is all boiled away. Explain.

2. What is the meaning of the statement that the heat of vaporization of liquid ammonia at 5° C. is 314 calories per gram?

3. After water has been brought to a boil, will eggs become hard any sooner when the flame is high than when it is low?

4. The hot water which leaves a steam radiator may be as hot as the steam which entered it. How, then, has the room been warmed?

5. Why are burns caused by steam so much more severe than burns caused by hot water of the same temperature?

6. In a certain radiator 2 kg. of steam at 100° C. condensed to water in 1 hr., and the water left the radiator at 90° C. How many calories were given to the room during the hour?

7. How many calories are required to convert 10 g. of ice at 0° C. into steam at 100° C.?

8. How many grams of steam at 100° C. must be condensed in 1 kg. of snow at 0° C. to convert the snow into water at 0° C.?

9. How may we obtain pure drinking water from sea water?

10. Explain why salt is thrown on icy sidewalks on cold winter days.

11. If pieces of ice are dropped into water maintained at 0° C., will the ice melt? Why? If a saturated brine solution has a temperature of 0° C. and ice is dropped into it, what will happen to the ice? to the temperature of the brine solution?

12. Give two reasons why an ocean freezes less easily than a lake.

13. When the salt in an ice-cream freezer unites with the ice to form brine, about how many calories of heat are used for each gram of ice melted? Where does it come from? If the freezing point of the salt solution were the same as that of the cream, would the cream freeze?

14. How many kilograms of ice can be formed from water at 0° C. by taking from the water enough heat to vaporize 10 kg. of ammonia? (Consider the heat of vaporization of liquid ammonia to be 314 calories per gram.)

STEAM ENGINES

234. The modern steam engine. Thus far in our study of the transformations of energy we have considered only cases in which mechanical energy was transformed into heat energy. In all heat engines we have examples of exactly the reverse operation, namely, the transformation of heat energy back into mechanical energy. How this is done may best be understood from a study of various modern forms of heat engines. The invention of the form of the steam engine which is now in use is due to James Watt (see opposite page 133), who, at the time of the invention (1768), was an instrument maker in the University of Glasgow.

The operation of such a machine can best be understood from the ideal diagram shown in Fig. 176. Steam generated in the boiler by the fire passes through the pipe S into the steam chest V, and thence through the passage N into the cylinder C, where its pressure forces the piston P to the left. It will be seen from the figure that as the driving rod R moves toward the left the so-called eccentric rod R', which controls the valve V, moves toward the right. Hence, when the piston has reached the left end of its stroke, the passage N will have

been closed, while the passage M will begin to admit steam, thus throwing the pressure from the right to the left side of the piston, and at the same time putting the right end of the cylinder, which is full of spent steam, into connection with the exhaust pipe E. This operation goes on continually, the rod R' opening and closing the passages M and N at just the proper moments to keep the piston moving back and forth

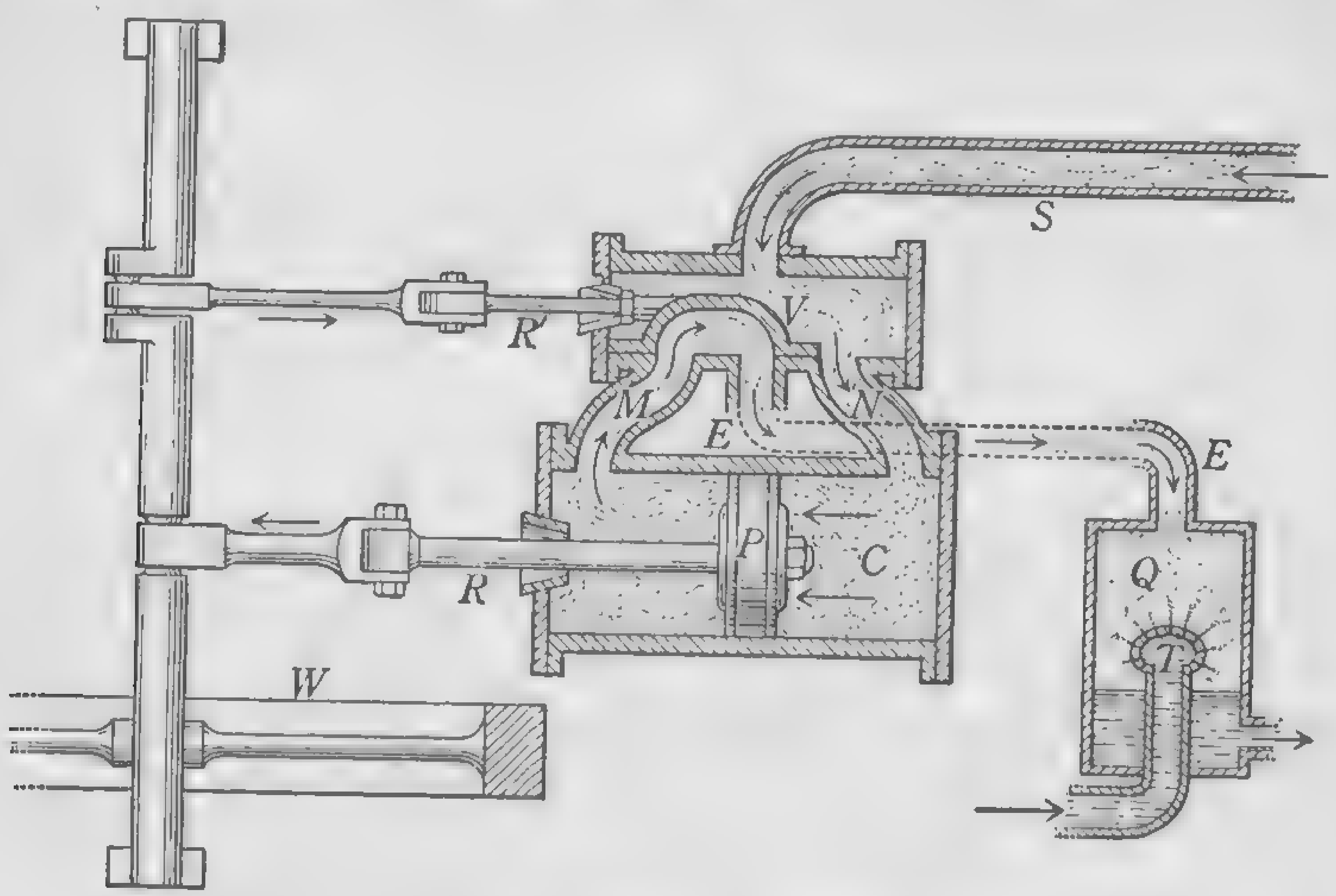
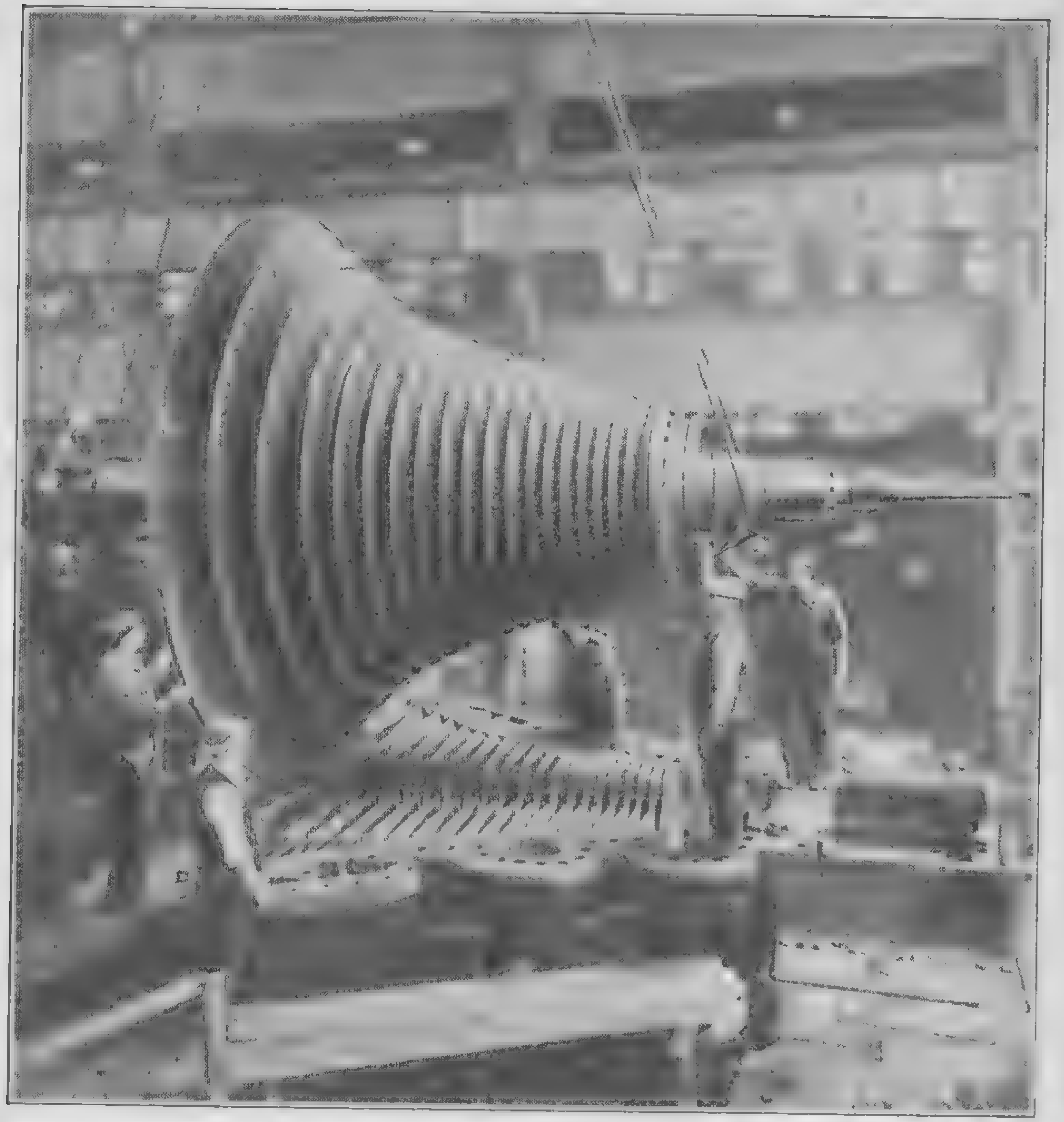


FIG. 176. Ideal diagram of a steam engine

throughout the length of the cylinder. In the actual engine the valve V is so constructed and adjusted that the supply of steam from the boiler is cut off after the piston has made a part of its full stroke, the rest of the stroke being completed under the diminishing expansive pressure of the steam within the cylinder. The shaft carries a heavy flywheel W, the great inertia of which insures constancy in speed. The motion of the shaft is communicated to any desired machinery by means of a belt which passes over the wheel W. Within the boiler the steam is at high pressure and high temperature (§ 225). The steam falls in temperature within the cylinder while doing the work of pushing the piston. *A steam engine*

SADI CARNOT (1796–1832)

Brilliant young physicist and engineer and discoverer at the age of twenty-eight of one of the most important principles in physics, the principle underlying the second law of thermodynamics. He exerted an enormous influence not only upon the development of the heat engine, but upon the whole of theoretical physics and chemistry. He died at the age of thirty-six, after contributions almost unequaled by anyone of his years



THE ROTOR OF A STEAM TURBINE

The great rotor of a 60,000-kilowatt steam turbine,— the latest and most efficient form of steam engine. The figure shows the enormous number of movable blades against which the steam impinges after being directed upon them at the most suitable angle by the stationary blades (half being shown below the rotor), which are arranged in rows alternating with the movable ones. The turbine can take in steam at a somewhat higher temperature and pressure than most steam engines and reject it at a somewhat lower temperature. This, in accordance with Carnot's principle, is what determines the efficiency. Experiments are now being made with turbines, using steam at 1200 pounds' pressure. Steam-turbine rotors revolve with a speed of from 200 to 30,000 R.P.M. The peripheral speed of the large wheel shown above is 12 miles per minute, or over 1000 feet per second. This turbine consumes 9650 pounds of steam per minute. (Courtesy of the General Electric Company)

is a mechanical device which accomplishes useful work by transforming heat energy into mechanical energy.

235. Condensing and noncondensing engines. In most stationary engines the exhaust E leads to a condenser which consists of a chamber Q, into which plays a jet of cold water T, and in which a partial vacuum is maintained by means of an air pump. In the best engines the pressure within Q is not more than from 3 to 5 centimeters of mercury, that is, not more than a pound to the square inch. Hence the condenser reduces the back pressure against that end of the piston which is open to the atmosphere from 15 pounds down to 1 pound per square inch and thus increases the effective pressure which the steam on the other side of the piston can exert.

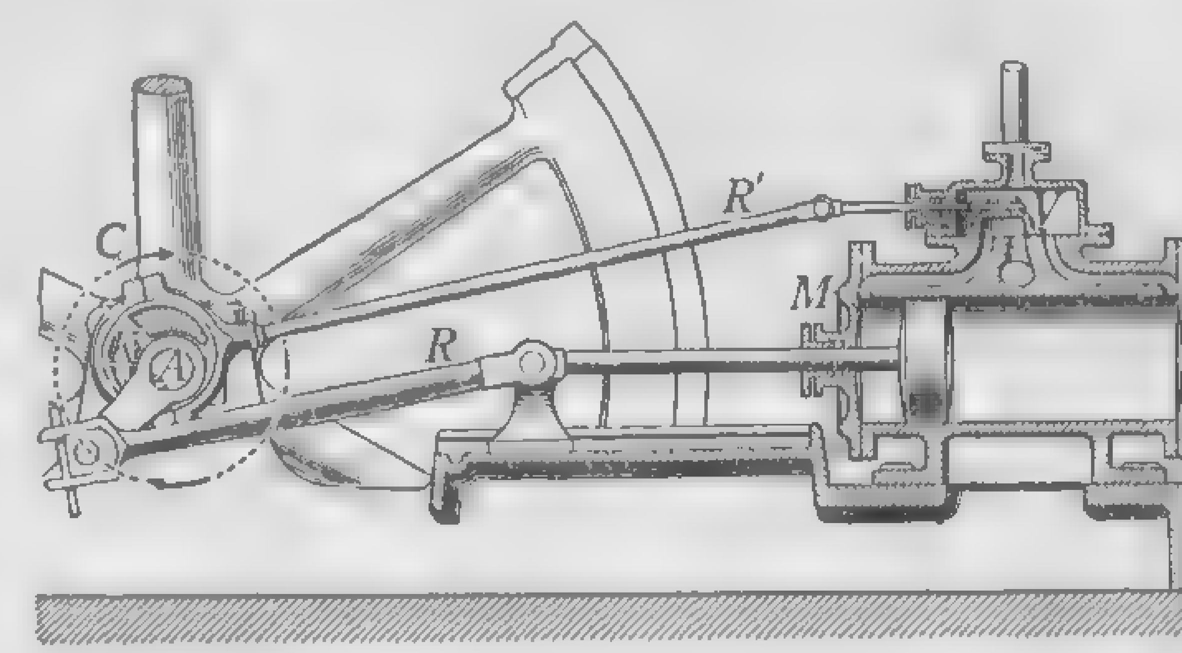


FIG. 177. The eccentric

236. The eccentric. In practice the valve rod R' is not attached as in the ideal engine indicated in Fig. 176, but motion is communicated to it by a so-called *eccentric.* This consists of a circular disk K (Fig. 177) rigidly attached to the axle but so set that its center does not coincide with the center of the axle A. The disk K rotates inside the collar C and thus communicates to the eccentric rod R' a back-and-forth motion which operates the valve V in such a way as to admit steam alternately through M and N at the proper time.

237. The boiler. When an engine is at work, steam is being removed very rapidly from the boiler; for example, a railway locomotive consumes from 3 to 6 tons of water per hour. It is therefore necessary to have the fire in contact with as large a surface as possible. In the tubular boiler this end is accomplished by causing the flames to pass through a large number of metal tubes immersed in water. The arrangement of the furnace and the boiler may be seen from the diagram of a locomotive shown in Fig. 178. (See early and modern types opposite page 132.)

238. The draft. In order to force the flames through the tubes B of the boiler a powerful draft is required. In locomotives this is obtained by running the exhaust steam from the cylinder C (Fig. 178) into the smokestack E through the blower F. The

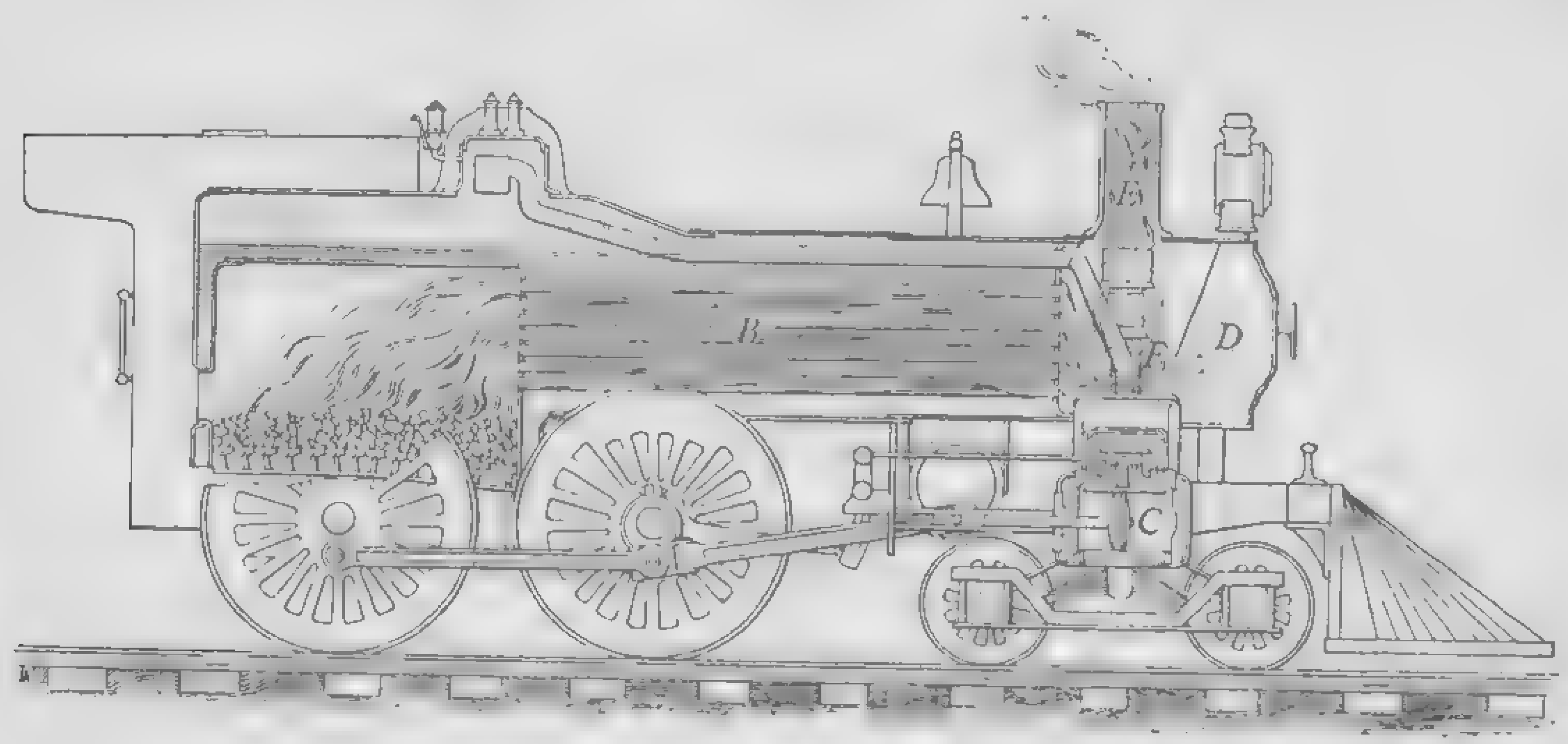


FIG. 178. Diagram of a locomotive

strong current through F draws with it a portion of the air from the smoke box D, thus producing within D a partial vacuum into which a powerful draft rushes from the furnace through the tubes B. The coal consumption of an ordinary locomotive is from one-fourth ton to one ton per hour.

In stationary engines a draft is obtained by making the smokestack very high. Since in this case the pressure which is forcing the air through the furnace is equal to the difference in the weights of columns of air of unit cross section inside and outside the chimney, it is evident that this pressure will be greater the greater the height of the smokestack. This is the reason for the immense heights given to chimneys in large power plants.

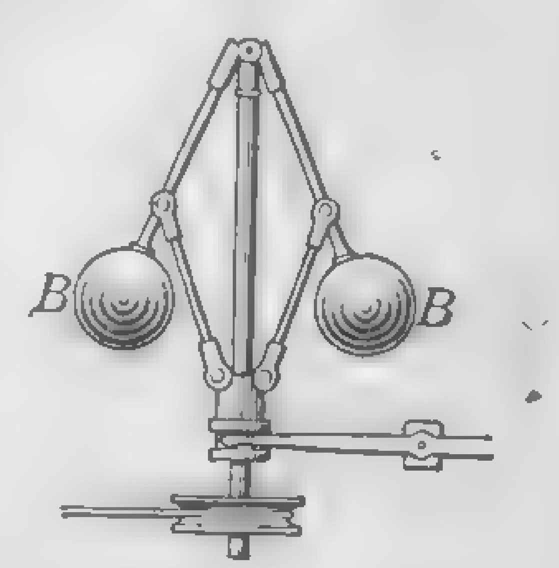


FIG. 179. The governor

239. The governor. Fig. 179 shows an ingenious device of Watt's, called a *governor*, for automatically regulating the speed with which a stationary engine runs. If it runs too fast, the heavy rotating balls B move apart and upward and in so doing operate a valve which reduces the speed by partially shutting off the supply of steam from the cylinder.

240. Compound engines. In an engine which has but a single cylinder the full force of the steam has not been spent when the cylinder is opened to the exhaust. The waste of energy which this entails is obviated in the compound engine by allowing the partially spent steam to pass into a second cylinder of larger area than the first. The most efficient of modern engines have three and sometimes four cylinders of this sort, and accordingly they are called *triple-expansion* or *quadruple-expansion engines*. Fig. 180 shows the relation between any two successive cylinders of a cross-compound engine. By automatic devices not differing in principle from the eccentric, valves C^1, D^2, and E^2 open simultaneously and thus permit steam from the boiler to enter the small cylinder A, while the partially spent steam in the other end of the same cylinder passes through D^2 into B, and the more fully exhausted steam in the upper end of B passes out through E^2. At the upper end of the stroke of the pistons P and P', C^1, D^2, and E^2 automatically close, while C^2, D^1, and E^1 simultaneously open and thus reverse the direction of motion of both pistons. These pistons are attached to the same shaft.

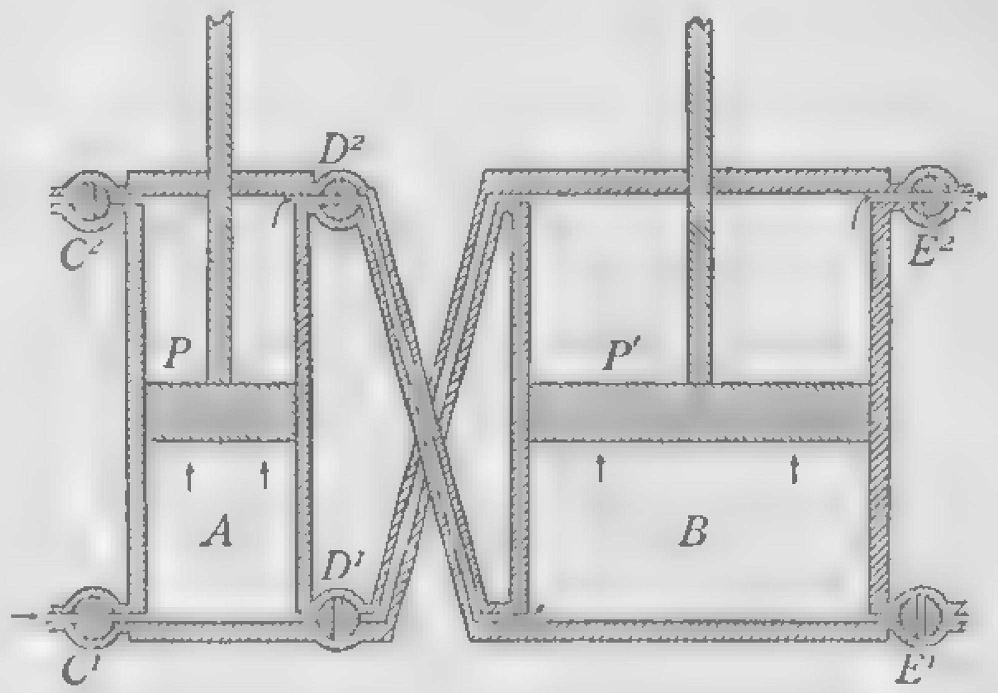


FIG. 180. Cross-compound engine cylinders

241. Efficiency of a steam engine. We have seen that it is possible to transform completely a given amount of mechanical energy into heat energy. This is done whenever a moving body is brought to rest by means of a frictional resistance. But the inverse operation, namely, that of transforming heat energy into mechanical energy, differs from this in that it is only a comparatively small fraction of the heat developed by combustion which can be transformed into work. For it is not difficult to see that in every steam engine at least a part of the heat must of necessity pass over with the exhaust steam into the condenser or out into the atmosphere. This loss is so great that even in an ideal steam engine not more than

about 25 per cent of the heat of combustion could be transformed into work. In some modern steam-generator plants in which oil is used as fuel and all heat losses minimized, an amazing running efficiency is maintained — actually $24\frac{1}{2}$ per cent of the heat value of the fuel being converted into electrical energy. The best locomotives utilize at most not more than 13 per cent. *The efficiency of a heat engine is defined as the ratio between the heat utilized, or transformed into work, and the total heat expended.* The efficiency of the best locomotive is, therefore, only about $\frac{13}{25}$, or 52 per cent, of the ideal limit.

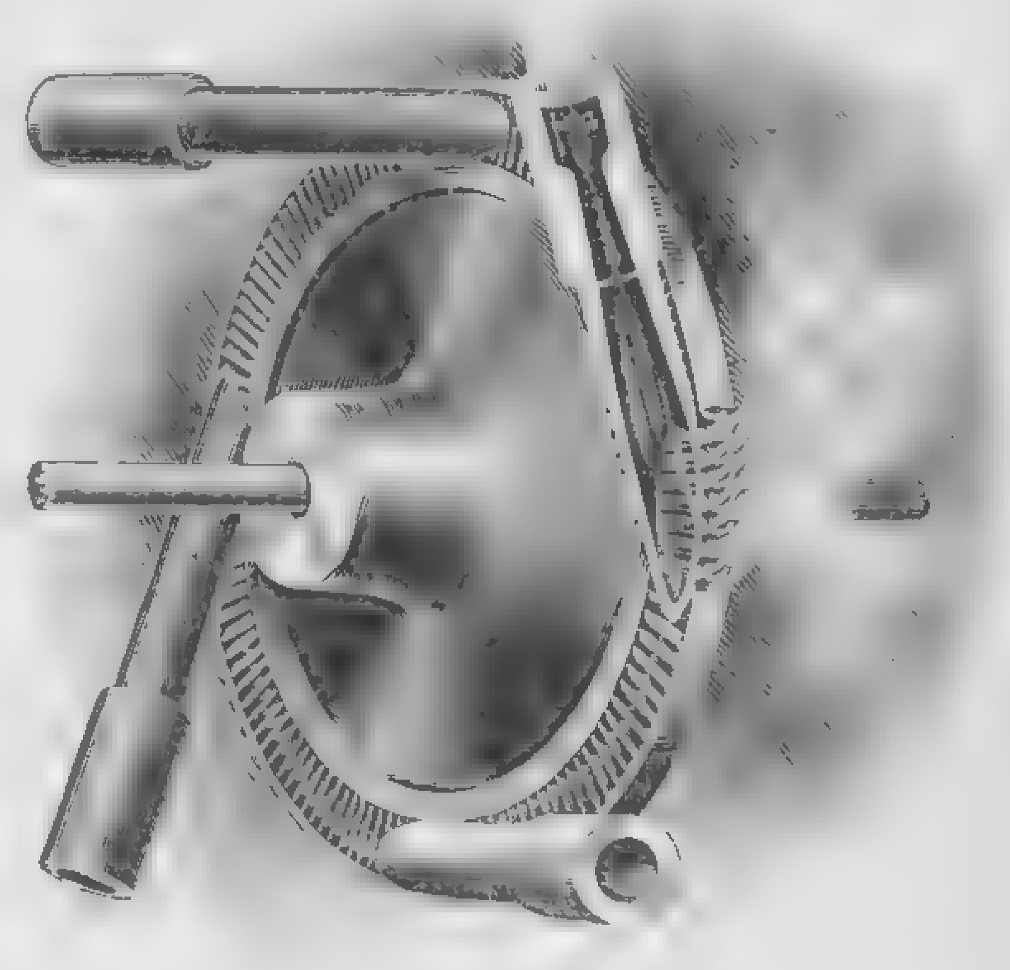


FIG. 181. The principle of the steam turbine

242. The steam turbine. The steam turbine (see opposite page 205) represents the latest development of the heat engine. In principle it is very much like the common windmill, the chief difference being that it is steam instead of air which is driven at a high velocity against a series of blades arranged radially about the circumference of the wheel that is set into rotation. The steam, however, unlike the wind, is always directed by nozzles at the angle of greatest efficiency against the blades (see Fig. 181). Furthermore, since the energy of the steam is far from spent after it has passed through one set of blades (such as that shown in Fig. 181), it is in practice always passed through a whole series of such sets (Fig. 182), every alternate row of which is rigidly attached to the rotating shaft, and intermediate rows are fastened to the immovable outer jacket of the engine and only serve as guides to redirect the steam at the most favorable angle against the next row of movable blades. In this way the steam is kept alternately bounding from fixed to movable blades until its energy is expended. The number of rows of blades is often as high as sixteen.

The transformation of heat energy into mechanical energy is due entirely to changes in momentum of the steam as it passes through the blade channels, whereas in the reciprocating steam engine it occurs through a statical pressure of the steam against the piston.

Turbines are at present coming rapidly into use, chiefly for large-power purposes. Their advantages over the reciprocating steam engine lie first in the fact that they run with almost no jarring, and therefore require much lighter and less expensive foundations, and secondly in the fact that they occupy less than one tenth the floor space of ordinary engines of the same capacity. Moreover, their efficiency is slightly higher than that of the best reciprocating engines, because a lower pressure can be maintained in the condenser. The highest speeds attained by vessels at sea, namely, about 40 miles per hour, have been made with the aid of steam turbines. One of the largest vessels which have thus far been launched, the *Berengaria*, 919 ft. long, 98 ft. wide, 100 ft. high (from the keel to the top of her ninth deck), having a total displacement of 57,000 tons and a speed of $22\frac{1}{2}$ knots, is driven by four steam turbines having a total horse power of 61,000. One of the immense rotors contains 50,000 blades and develops 22,000 H.P.

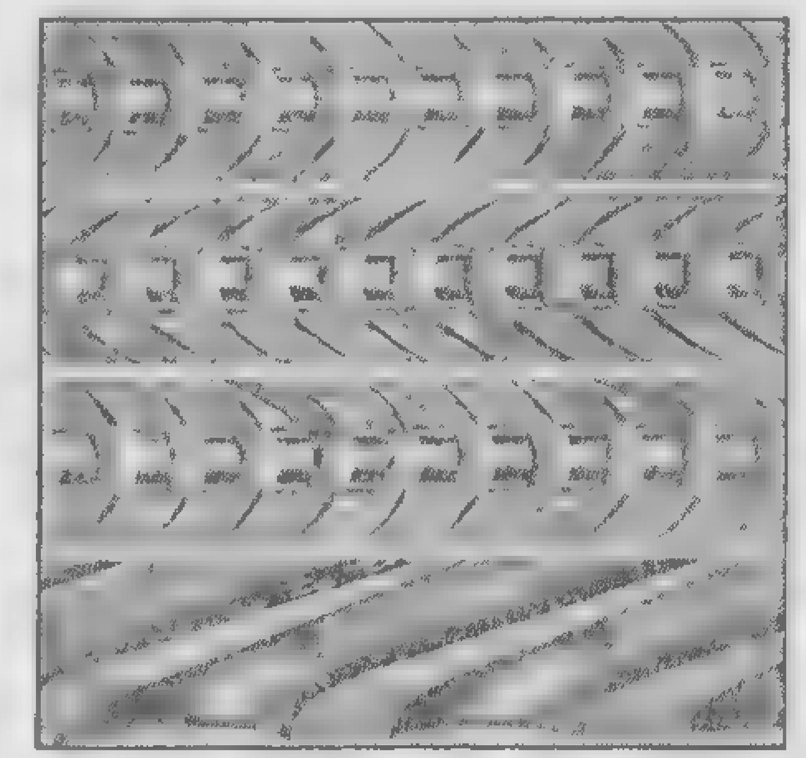


FIG. 182. Path of steam in Curtis's turbine

SUMMARY. A steam engine transforms heat energy into mechanical energy through the use of superheated steam, which cools during the act of producing motion or doing work.

A condensing engine increases the effective boiler pressure about 14 pounds per square inch.

A compound engine is more efficient than one having a single cylinder because in the former a larger percentage of the total expansive force of the steam can be utilized before final exhaust.

Turbine engines occupy relatively small floor space, are very free from vibrations, and utilize most fully the expansive power of the steam.

QUESTIONS AND PROBLEMS

1. How does the temperature of the steam within a locomotive boiler compare with its temperature at the moment of exhaust? Explain.

2. On the drive wheels of locomotives there is a mass of iron opposite the point of attachment of the drive shaft. Why is this necessary?

3. Why does not the water in a locomotive boil at 100° C.?

4. When the steam gauge of a locomotive records 250 lb. per square inch, the steam is at a temperature of 406° F. Explain how the steam produces this great pressure.

5. What pull does a 1000 H.P. locomotive exert when it is running at 25 mi. per hour and exerting its full horse power?

6. If the average pressure in the cylinder of a steam engine is 10 kilos to the square centimeter, and the area of the piston is 427 sq. cm., how much work is done by the piston in a stroke of length 50 cm.? How many calories did the steam lose in this operation?

Internal-Combustion Engines

243. Principle of the internal-combustion engine. Let two iron or steel wires be pushed through a cork stopper and their ends *s* brought near together ($\frac{1}{32}$ in. will do) (Fig. 183). By displacement of water introduce into the inverted bottle enough illuminating gas to fill it about one-fifth, allowing the remainder of the water to run out, or with an atomizer spray into the bottle a small amount of benzine or gasoline (the amount to use can be determined by trial), insert the stopper, and bring the tips of the heavily insulated wires leading from an induction coil to the under side of the wires *a*, *b*. A spark will pass at *s*; and, if the mixture is not too "rich" or too "lean," a violent explosion will occur, throwing the stopper as high as the ceiling. (*A heavy round bottle must be used for safety. Wrap it well in wire gauze.*)

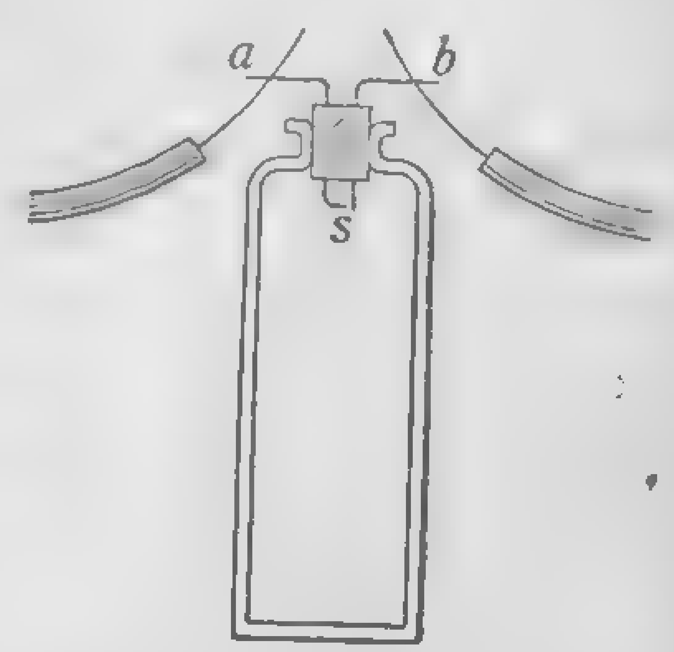
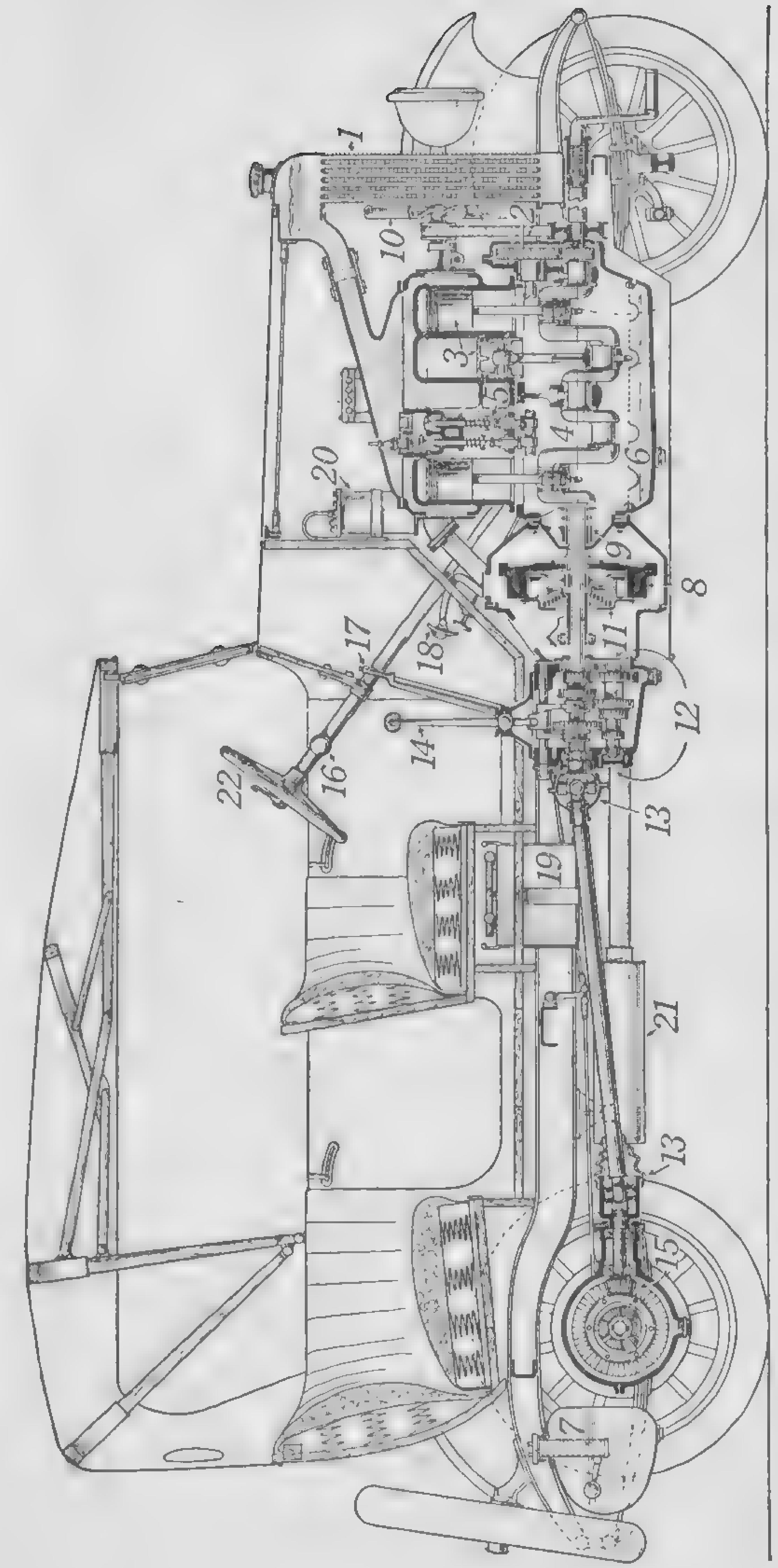
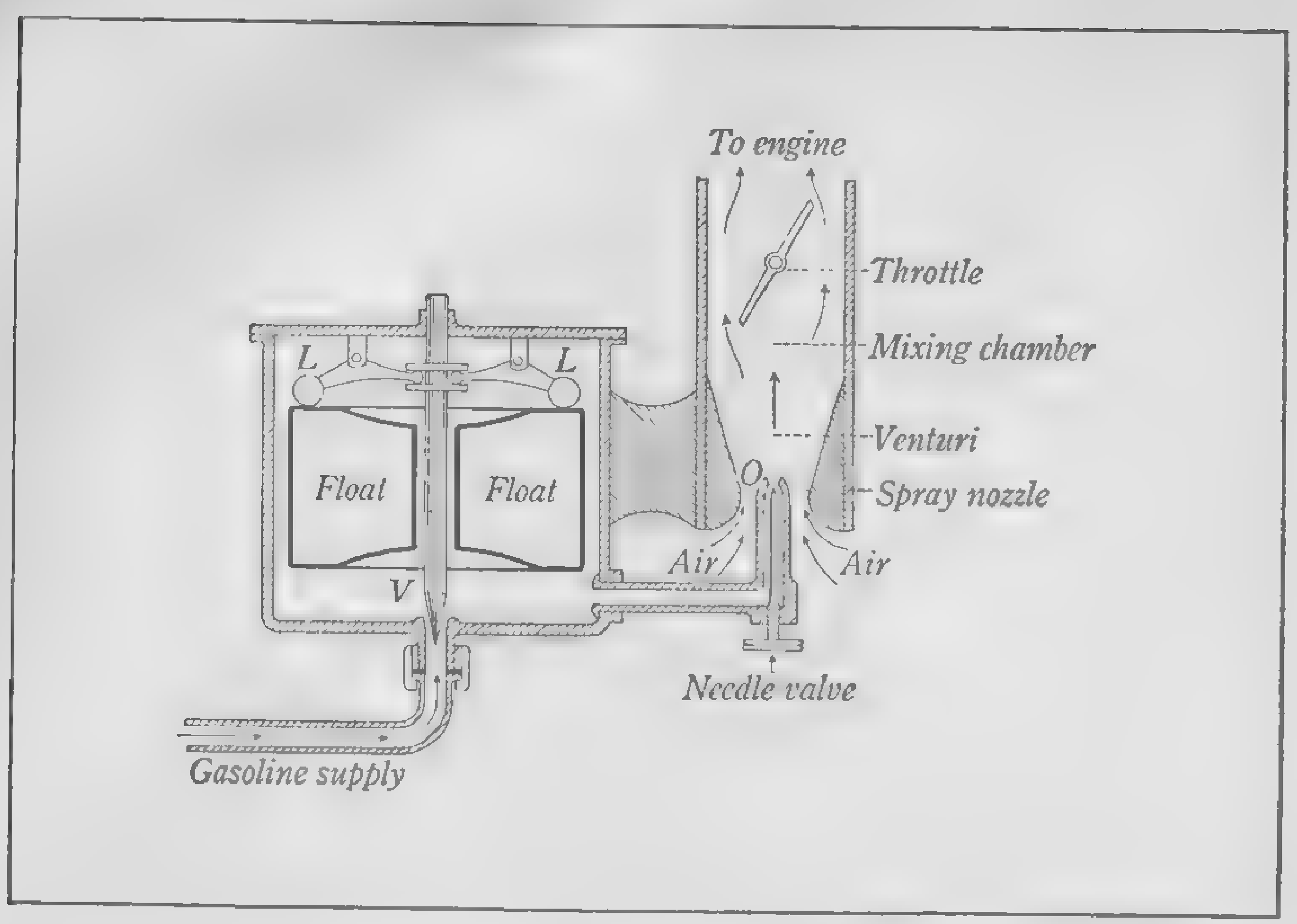


FIG. 183. A mixture of gasoline vapor and air will explode

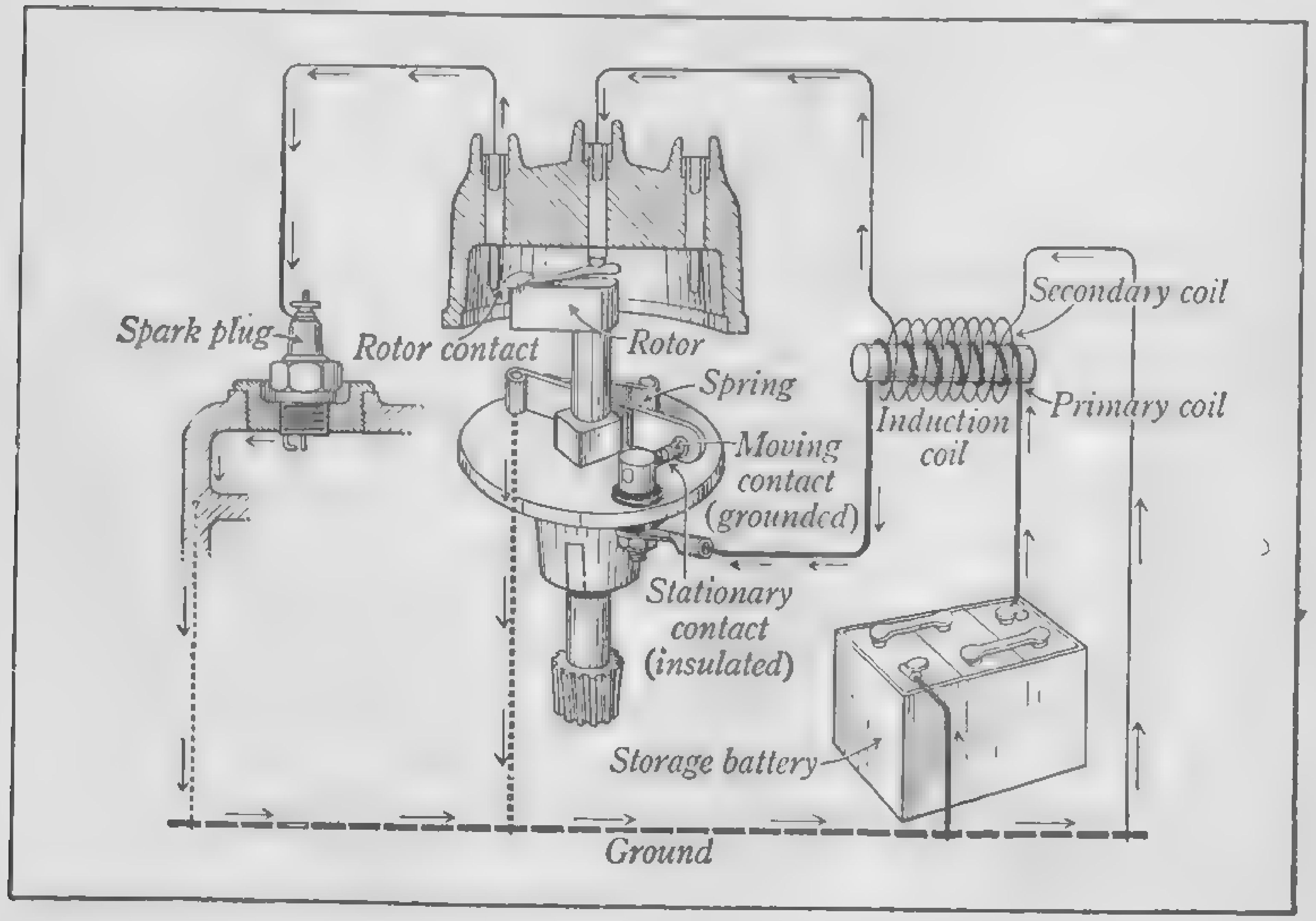


SECTION OF A MODERN AUTOMOBILE, SHOWING THE PRINCIPAL MECHANICAL PARTS

1, radiator; *2*, timing gears to operate valves in proper relation to position of pistons; *3*, pistons; *4*, crank shaft; *5*, valve stems and push rods operated by cams on the cam shaft; *6*, oil reservoir; *7*, gasoline tank; *8*, flywheel; *9*, main rear bearing; *10*, cooling fan; *11*, clutch for connecting the crank shaft of the engine to the transmission; *12*, transmission; *13*, universal joints; *14*, gear-shift lever; *15*, main driving gear and pinion; *16*, electric control switch; *17*, emergency-brake lever; *18*, service-brake foot lever; *19*, storage battery; *20*, vacuum feed system; *21*, muffler; *22*, steering wheel



THE CARBURETOR



A BATTERY IGNITION SYSTEM USING A NON-VIBRATING INDUCTION COIL, A BREAKER, AND A ROTATING DISTRIBUTOR

Within the last two decades gas engines have become quite as important a factor in modern life as steam engines (see opposite pages 89, 210, and 217.) Such engines are driven by properly timed explosions of a mixture of gas and air occurring within the cylinder.

Fig. 184 is a diagram illustrating the four stages into which it is convenient to divide the complete cycle of operations which goes on within each cylinder of such an engine.

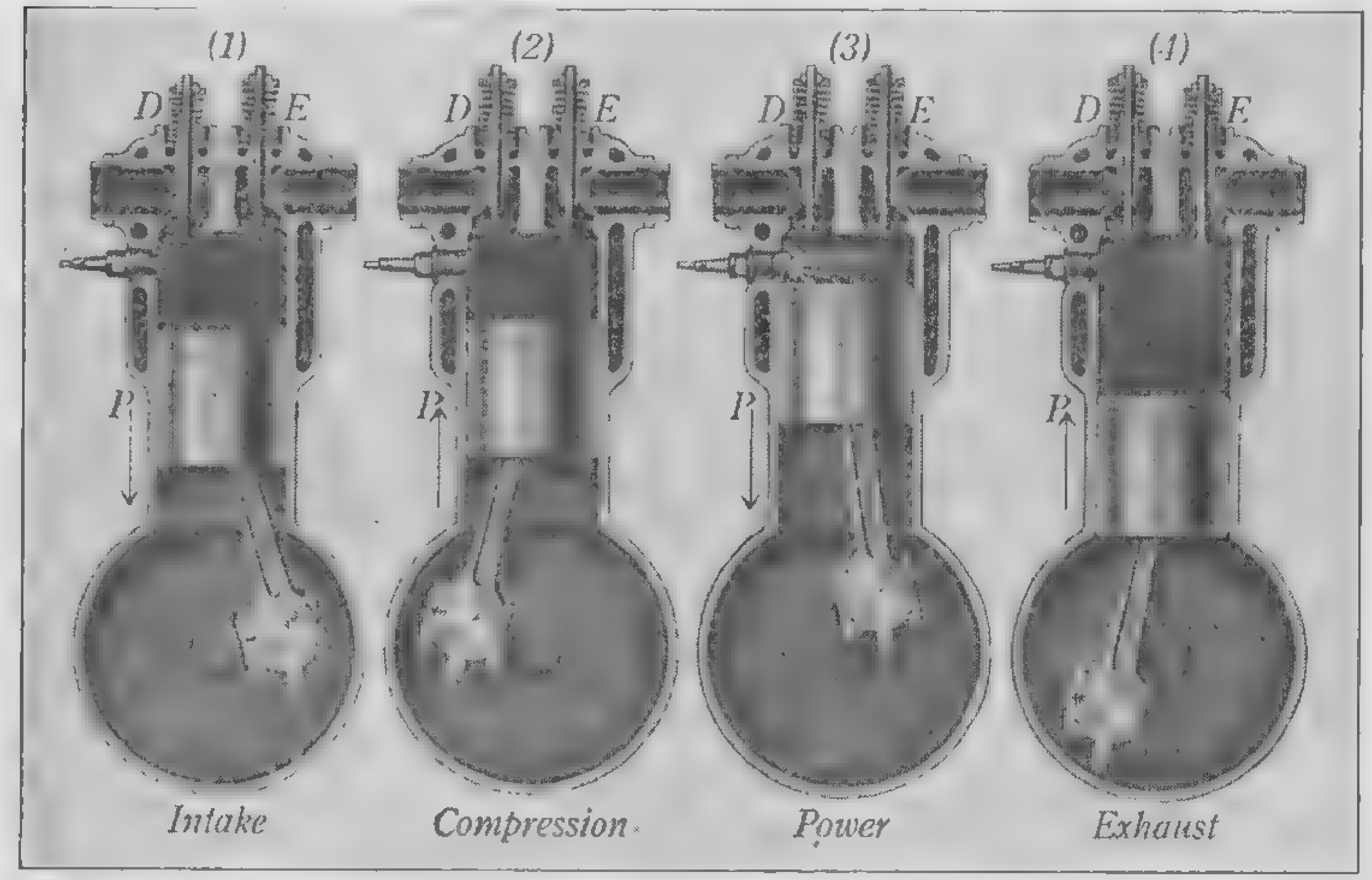


FIG. 184. Principle of the gas engine

Suppose that the engine has already been set in motion. As the piston P moves down in the first stroke (see (1)) the intake valve D is forced open by a cam on the rotating cam shaft (see opposite page 210) and an explosive mixture of gas and air is drawn into the cylinder through D. As the piston rises (see (2)), valve D is forced shut by a spiral spring and the mixture of gas and air is compressed into a small space in the upper end of the cylinder. An electric spark ignites the explosive mixture, and the force of the explosion drives the piston violently down (see (3)). At the beginning of the return stroke (see (4)) the exhaust valve E is forced open, and as the

piston moves up, the spent gaseous products of the explosion are forced out of the cylinder. The initial condition is thus restored and the cycle represented by the four strokes begins over again.

Since it is only during the third stroke that the engine is receiving energy from the exploding gas, the flywheel is always made very heavy, so that the energy stored up in it in the third stroke may keep the machine running with little loss of speed during the other three parts of the cycle.

The efficiency of the gas engine is often as high as 30 per cent, or greatly in excess of that of the best steam engines. Furthermore, it is free from smoke, is very compact, and may be started at a moment's notice. On the other hand, the fuel (gas or gasoline) is comparatively expensive. Most automobiles are run by gasoline engines, chiefly because the lightness of the engine and of the fuel to be carried are here considerations of great importance. It has been the development of the light and efficient gas engine which has made possible man's recent conquest of the air through the use of the airplane and airship.

244. The automobile. The plate opposite page 210 shows the principal mechanical features of the automobile in their relation to one another. It will be seen that the cylinders of the engine are surrounded by water jackets which form part of a circulating system. The heat of the engine is carried by convection currents in this water to the radiator, where it is lost to the atmosphere through the air currents produced in part by a revolving fan (*10*). Unless some means were provided for cooling a gas engine, it would become so overheated that the pistons would stick fast. The power of the engine is transmitted to the rear axle through the clutch (*11*), the transmission (*12*), and the differential gearing.

245. The clutch and the transmission. Since a gas engine develops its power by a series of violent explosions within the cylinders, it is clear that it cannot start with a load as does the steam engine. In starting an automobile it is necessary first that the engine acquire a reasonable speed and that the power be ap-

plied gradually to the rear axle by the use of a friction clutch (*11*); otherwise the engine will stall. The shaft of the engine has upon its rear end a flywheel which, in the *cone* clutch is turned to a conical shape inside. Close to this but attached to the transmission shaft is the clutch plate, a heavy disk faced with leather, which fits the inside of the flywheel and is pressed into it by a spring sufficiently strong to prevent any slipping when the clutch is engaged. The driver throws out the clutch by depressing a lever with his foot. In the *disk* clutch (the form most commonly used) the bearing surfaces are two series of disks, one revolving with the engine shaft, the other with the transmission.

The amount of work done by a gas engine in a minute depends upon the work done by each explosion multiplied by the number of explosions per minute. Therefore it can develop its full power only while revolving rapidly. In hill climbing, for example, the speed of the engine must be great while that of the car is comparatively small. To meet this requirement a system of reduction gears called the transmission (*12* and Fig. 185) is used to make the number of revolutions of the driving shaft less than that of the crank shaft (*4*) of the engine. In Fig. 185 (1) the gears are in *neutral*, gears *1* and *2* being always in mesh. By use of the gear-shift

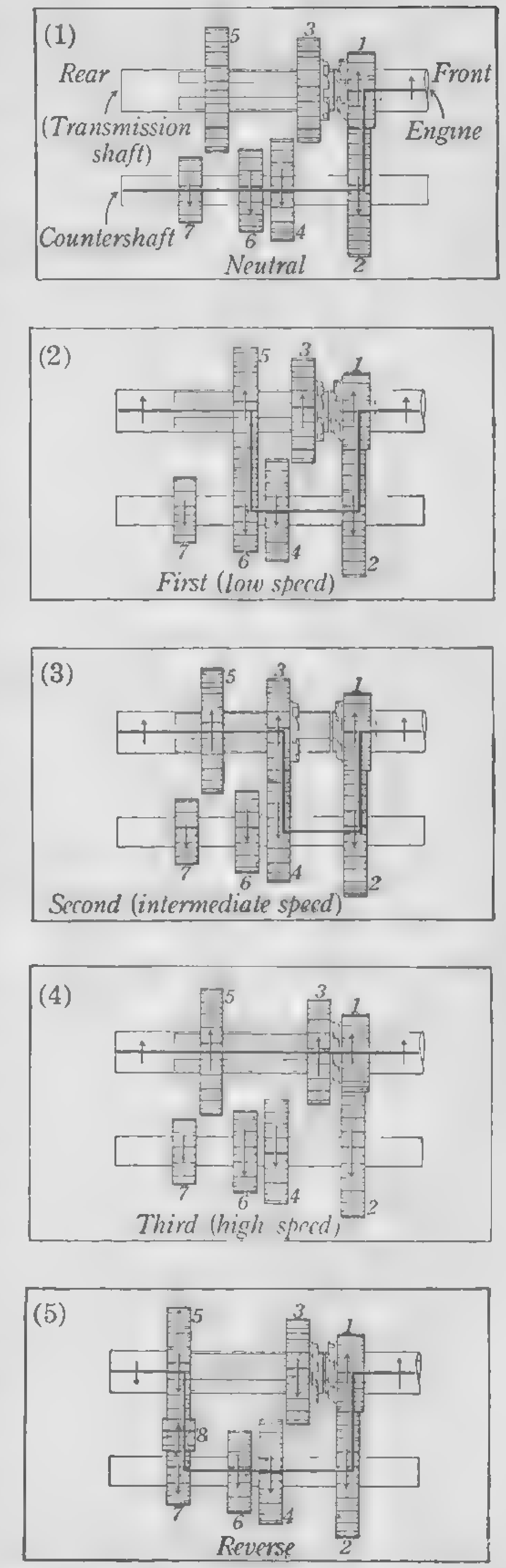


FIG. 185. Automobile transmission

lever (*14*) gears *3* and *5* (Fig. 185) are made to slide upon a square shaft. Before shifting the gears the clutch is released to disconnect the power of the motor from the driving shaft; and, to avoid a clash when meshing the gears on the transmission shaft with those on the countershaft, care should be taken that they revolve at about the same speed. Fig. 185 (2) shows the low-speed connection. In shifting to second speed (Fig. 185 (3)) the clutch is released, gear *5* is thrown into neutral, and finally gear *3* is meshed with *4*, after which the clutch is allowed to grip. In going to high speed (Fig. 185 (4)) gear *3* is shifted through neutral to engagement with gear *1*. This connects the crank shaft of the engine directly to the driving shaft so that the two revolve at the same speed. For the reverse (Fig. 185 (5)) an eighth gear simultaneously engages *5* and *7*. Such an interposition of a third gear wheel between *5* and *7* obviously reverses the direction of rotation of the driving shaft.

246. The differential. An automobile is driven by power applied to the rear axle. This requires the axle to be in two parts with a *differential* between, so that in turning corners the outer wheel may revolve faster than the inner. It will be seen from the large drawing opposite page 210, and from Fig. 186, that the pinion attached to the driving shaft rotates the main bevel gear *B*, to which are rigidly attached the differential gears *1* and *2*. The left axle is directly connected to gear *3*, and only indirectly connected to the main bevel gear *B* through gears *1* and *2*. In running straight both rear wheels revolve at the same rate; therefore, while gears *3* and *4* and the main bevel gear are revolving at the same speed they carry around with them pinions *1* and *2*, which are now, however, not revolving on their bearings. When the car is turning a corner, gears *3* and *4* are turning at *different* rates; hence pinions *1* and *2* are not only carried around by the main bevel gear but at the same time are revolved in opposite directions on their bearings.

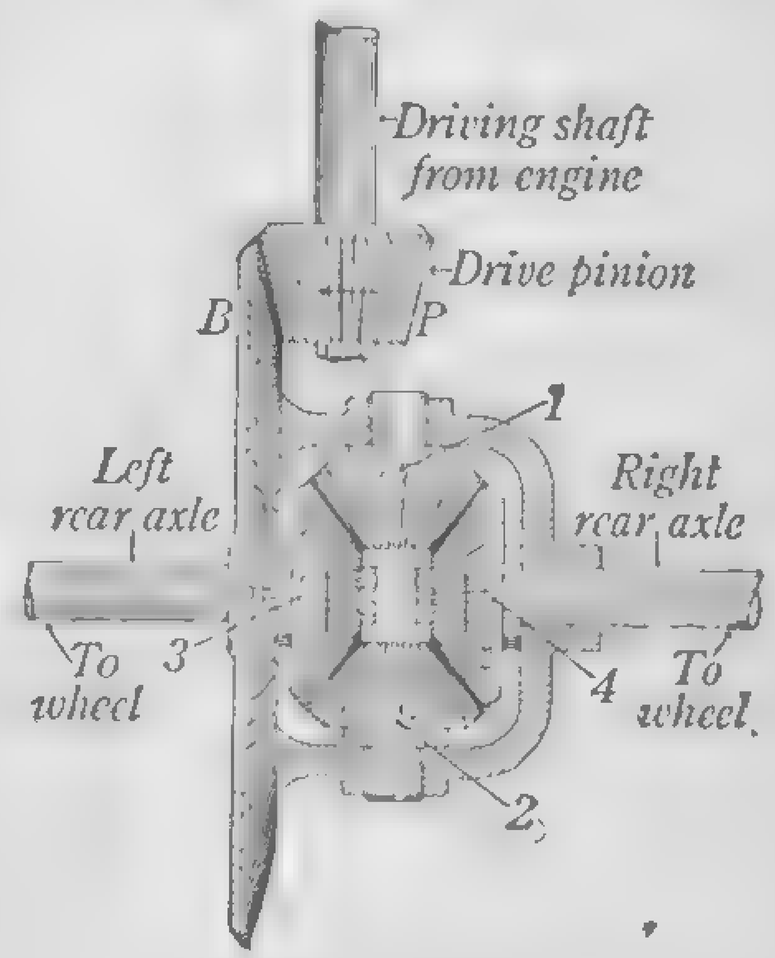


FIG. 186. The differential

247. The carburetor. The carburetor is a device for converting liquid gasoline, kerosene, etc. into spray and mixing it with air in proper proportions for complete combustion. The simple principle of carburetion is shown in the upper diagram opposite page 211. Liquid gasoline comes through the supply pipe and enters the float chamber through the valve *V*. By acting on the levers *L* the float closes the valve *V* when the gasoline reaches a certain level. From the float chamber the gasoline passes to the spray nozzle *O*. While the engine is running, the downward movement of the pistons in stroke (1) (Fig. 184) causes air to move swiftly past the spray nozzle into the region called the *venturi*, where the jet of gasoline is emerging from *O*. The spray of fuel thus formed intermingles with air in the mixing chamber and passes by the throttle to the engine as a highly explosive mixture.

248. The ignition. The lower diagram opposite page 211 illustrates the principle of battery ignition which is in extensive use on automobiles. A low-tension current, usually of from 6 to 8 volts, passes from a storage battery through the primary coil of an induction coil, through a moving contact, and thence through the framework of the car to the battery. While the engine is running a rotor (see diagram) makes successive contacts with the 4 or more terminals connected to the 4 or more spark plugs. The mechanism is so timed, or adjusted, that at the right instant for the explosive mixture to be ignited, and while the rotor is touching the proper rotor contact, the cam separates the grounded moving contact from the stationary insulated contact, thus breaking the primary circuit to produce a momentary high-tension current in the secondary of the induction coil. In this way a spark is produced at the terminals of each spark plug as shown in Fig. 184 (3). As many rotor contacts and spark plugs are employed as there are cylinders in the engine.

Since the power stroke of the piston occurs but once in two revolutions of the crank shaft, it is necessary that the crank shaft revolve twice while the cam shaft revolves but once. This, as shown in *2* of the diagram opposite page 210, is accomplished by having the crank shaft geared to the cam shaft in a velocity ratio of 2 to 1.

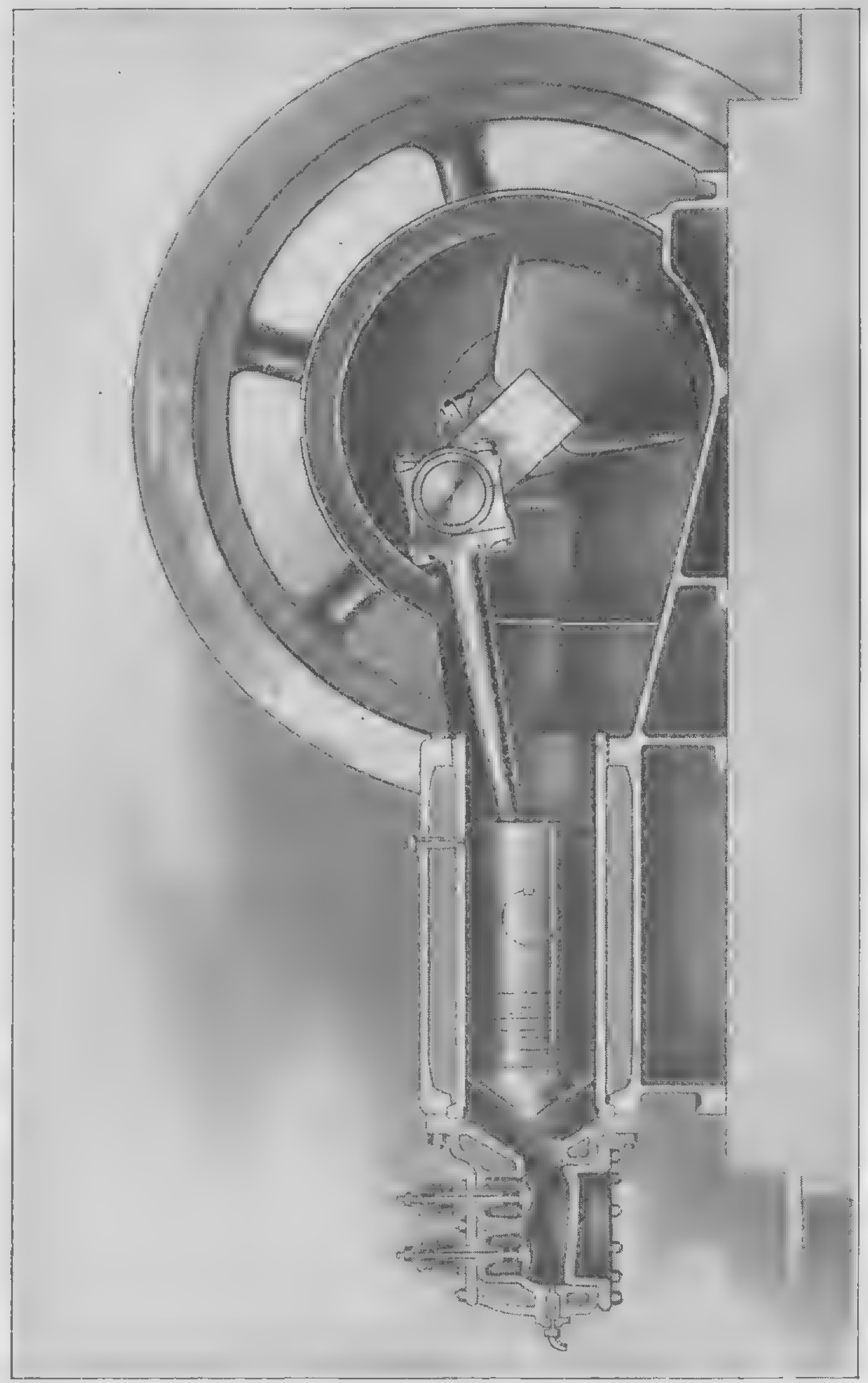
The explosive mixture requires a very short but measurable time for combustion; hence the full force of the explosion occurs a short time *after* the spark ignites the mixture. Therefore, at high speed the spark should occur a little earlier with reference to

the position of the piston than at low speed. The spark is usually *advanced* or *retarded* by slightly rotating the plate to which the moving and stationary contacts are attached.

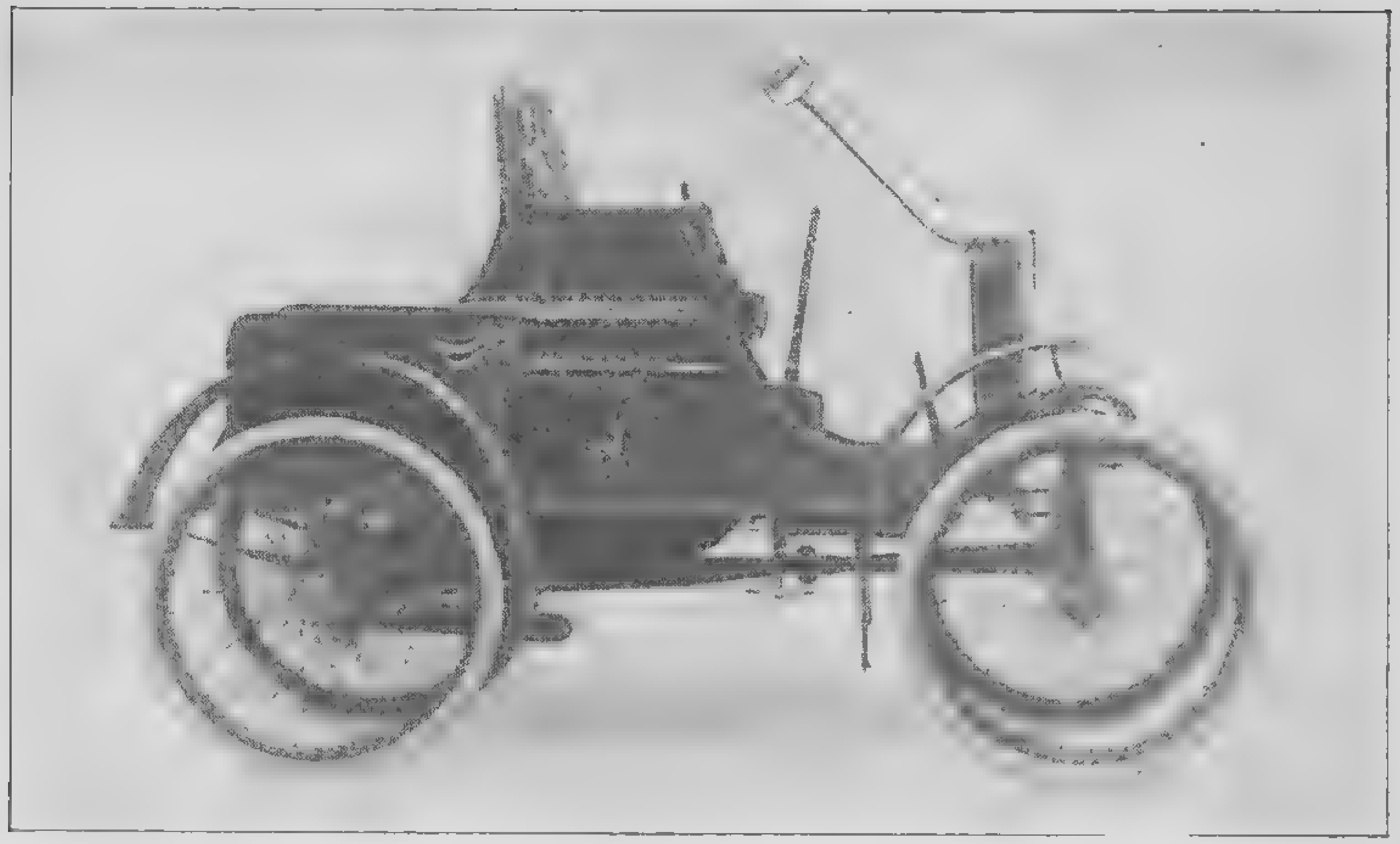
249. The Diesel and the semi-Diesel engine. The Diesel engine is a form of internal-combustion engine which depends for ignition of the fuel upon the heat developed by very high compression of air within its cylinder. Into this highly compressed and very hot air the oil spray is injected as a stream under still higher pressure during the first part of the power stroke and burns non-explosively, maintaining during this part of the stroke a pressure which is practically of constant value. The pressure then falls off during the remainder of the stroke.

In the semi-Diesel engine (shown on opposite page) the air is not compressed to as many hundred pounds to the square inch as in the full-Diesel type and the oil burns much more rapidly, taking on to some extent the characteristics of an explosion. In the diagram two valves (the air valve and the exhaust valve) are shown immediately above the small compartment called the *vaporizer*. During the "suction" stroke to the right a cylinderful of air is driven in through the air valve by the outside pressure and then compressed into the vaporizer during the return stroke. Near the instant of maximum compression atomized oil is forced into the intensely hot air, where it ignites and causes the power stroke. Semi-Diesel engines are widely used because they are reliable, simple in construction, and combine many of the best features of both the Diesel engine and the explosive gas engine.

The full-Diesel engine is more complex, but is also reliable, economical, and adapted to a wide range of fuels from kerosene through heavy oils to tar spray. They are used on submarines and for a great variety of purposes on land, and are increasingly coming into use on large merchant ships. They may, to a large extent, replace steam locomotives, especially for short hauls and for use in arid regions. The *Gripsholm*, a 23,500-ton ship of the Swedish-American Line is driven by



A SEMI-DIESEL OIL ENGINE



A PRIMITIVE AND A MODERN AUTOMOBILE

The upper picture shows a typical automobile of 1899. It had a 1-cylinder engine of about 9 H.P. and a wheel base of 72 inches. The drive was through a belt, and changes in speed were accomplished by slipping the belt. The lower picture shows a modern 7-passenger, 8-cylinder sedan limousine. The engine develops 80 H.P. (Courtesy of the Packard Motor Car Company)

two full-Diesel engines, each developing 17,000 H.P. at 125 revolutions per minute. Her speed is $17\frac{3}{4}$ knots.

SUMMARY. An internal-combustion engine has the heat for running it developed inside the cylinders, not outside, as in the case of the steam engine. Its high efficiency is due to the very high temperature thus obtained in the cylinder.

In the four-stroke type of gas engine the cycle consists of intake, compression, power, exhaust.

The principal mechanical parts of an automobile are the engine (including carburetor, ignition system, and cooling system), the clutch, the transmission, and the differential.

QUESTIONS AND PROBLEMS*

1. Why is a gas engine called an internal-combustion engine?

2. Why do gas engines have flywheels? Why is a one-cylinder stationary gas engine of the four-stroke type (such as are commonly used for small-power purposes) especially in need of a flywheel?

3. What amount of useful work did a gasoline engine working at an efficiency of 25 per cent do in using 100 lb. of gasoline containing 18,000 B.T.U. per pound?

4. Why will an automobile go up a hill in low gear (crank shaft revolving rapidly) when it would stall in high gear (crank shaft revolving slowly)?

5. Suppose the rear wheels of an automobile were keyed fast to a continuous axle (no differential), what would be the effect on wear of rear tires in turning corners? Explain.

* Supplementary questions and problems for Chapter X are given in the Appendix.

CHAPTER XI

THE TRANSFERENCE OF HEAT

Conduction

250. Conduction in solids. If one end of a short metal bar is held in the fire, the other end soon becomes too hot to hold; but if the metal rod is replaced by one of wood or glass, the end away from the flame is not appreciably heated.

This experiment and others like it show that nonmetallic substances possess much less ability to conduct heat than do metallic substances. But although all metals are good conductors as compared with nonmetals, they differ widely among themselves in their conducting powers.

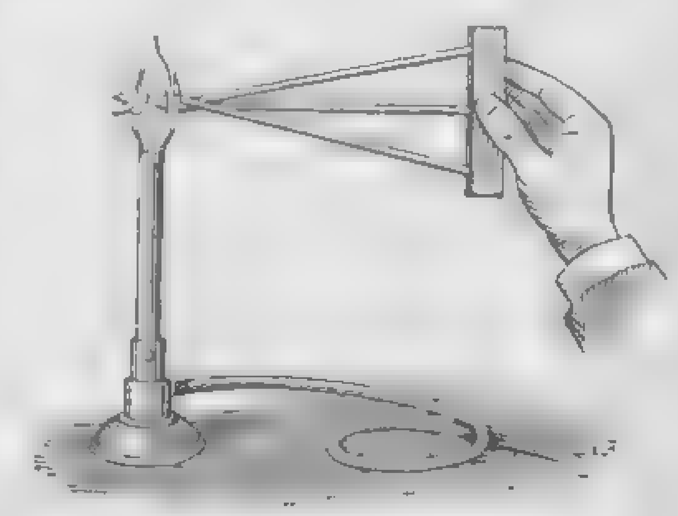


FIG. 187. Differences in the heat conductivities of metals

Let copper, iron, and German-silver wires 50 cm. long and about 3 mm. in diameter be twisted together at one end as in Fig. 187, and let a Bunsen flame be applied to the twisted ends. Let a match be slid slowly from the cool end of each wire toward the hot end, until the heat from the wire ignites it. The copper will be found to be the best conductor and the German silver the poorest.

In the following table some common substances are arranged in the order of their heat conductivities. The measurements have been made by a method not differing in principle from that just described. For convenience, silver is taken as 100.

Silver	100	Tin	15	Mercury	1.5
Copper	74	Iron	12	Ice	.21
Aluminum	48	Lead	8.5	Glass	.15
Brass	27	German silver	6.3	Hard rubber	.04

251. Conduction in liquids and gases. Let a small piece of ice be held by means of a glass rod in the bottom of a test tube full of ice water. Let the upper part of the tube be heated with a Bunsen burner as in Fig. 188. The upper part of the water may be boiled for some time without melting the ice. Water is evidently, then, a very poor conductor of heat. The same thing may be shown more strikingly as follows: The bulb of an air thermometer is placed only a few millimeters beneath the surface of water contained in a large funnel arranged as in Fig. 189. If now a spoonful of ether is poured on the water and set on fire, the index of the air thermometer will show scarcely any change, in spite of the fact that the air thermometer is a very sensitive indicator of changes in temperature.

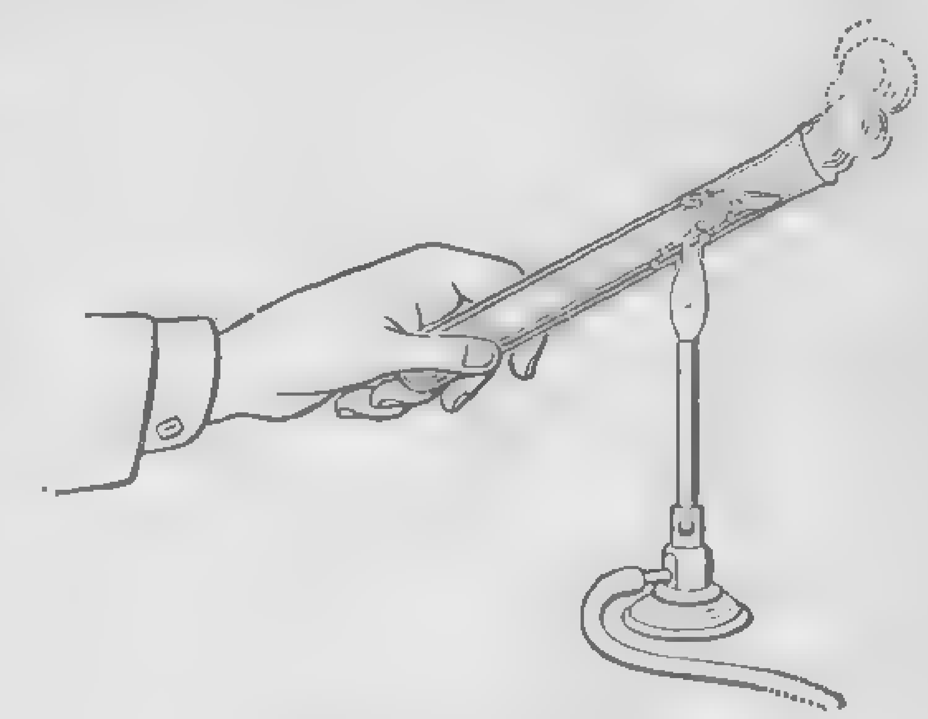


FIG. 188. Water a nonconductor

Careful measurements of the conductivity of water show that it is only about $\frac{1}{1200}$ that of silver. The conductivity of gases is even less, not amounting on the average to more than $\frac{1}{25}$ that of water.

252. Conductivity and sensation. It is a fact of common observation that on a cold day in winter a piece of metal feels much colder to the hand than a piece of wood, notwithstanding the fact that the temperature of the wood must be the same as that of the metal. On the other hand, if the same two bodies had been lying in the hot sun in midsummer, the wood might be handled without discomfort, but the metal would be uncomfortably hot. The explanation of these phenomena is found in the fact that the iron, being a much better conductor than the wood, removes heat from the hand much more rapidly in winter, and imparts heat to the

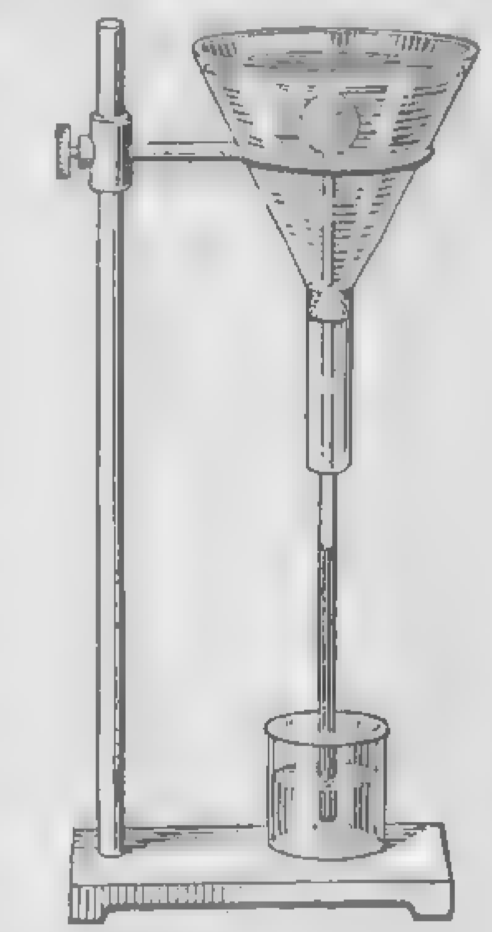


FIG. 189. Burning ether on the water does not affect the air thermometer

hand much more rapidly in summer, than does the wood. In general, the better a conductor the hotter it will feel to a hand colder than itself, and the colder to a hand hotter than itself. Thus, in a cold room oilcloth, a fairly good conductor, feels much colder to the touch than a carpet, a comparatively poor conductor. For the same reason linen clothing feels cooler to the touch in winter than woolen goods.

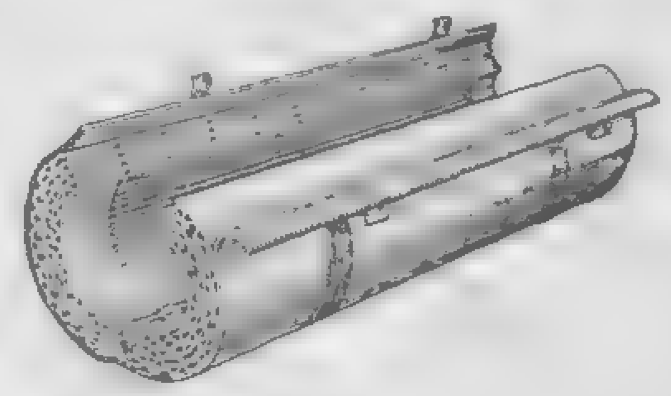


FIG. 190. Steam-pipe covering

253. The rôle of air in nonconductors. Feathers, fur, felt, etc. make very warm coverings, because they are very poor conductors of heat and thus prevent the escape of heat from the body. Their poor conductivity is due in large measure to the fact that they are full of minute spaces containing air, and gases are the best nonconductors of heat. It is for this reason that freshly fallen snow is such an efficient protection to vegetation. Farmers always fear for their fruit trees and vines when there is a severe cold snap in winter, unless there is a coating of snow on the ground to prevent a deep freezing. The cellular structure of steam-pipe covering (Fig. 190) utilizes the nonconducting nature of air. (See opposite p. 226.)

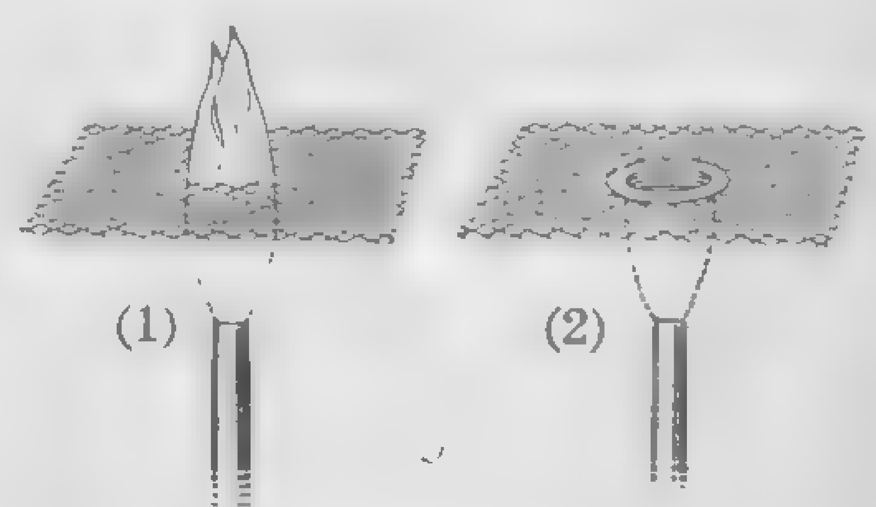


FIG. 191. A flame will not pass through wire gauze

254. The Davy safety lamp. Let a piece of copper-wire gauze be held above an open gas jet and a match applied above the gauze. The flame will be found to burn above the gauze as in Fig. 191 (1), but it will not pass through to the lower side. If it is ignited below the gauze, the flame will not pass through to the upper side but will burn as shown in Fig. 191 (2).

The explanation is found in the fact that the gauze conducts the heat away from the flame so rapidly that the gas on the other side is not raised to the temperature of ignition.

Safety lamps used by miners are completely incased in gauze, so that if the mine is full of inflammable gases, they are not ignited outside the gauze by the lamp.

SUMMARY. **Metals are the best conductors, gases the poorest.**

Of two hot bodies, the better conductor feels the hotter; of two cold bodies, the better conductor feels the colder.

The nonconducting power of loosely constructed bodies is due chiefly to the air they contain. One of the best of these is siloxicon (an infusorial siliceous earth).

QUESTIONS AND PROBLEMS

1. If the ice in a refrigerator is wrapped up in blankets, what is the effect on the ice? on the refrigerator?

2. Why do firemen wear flannel shirts in summer to keep cool, and in winter to keep warm?

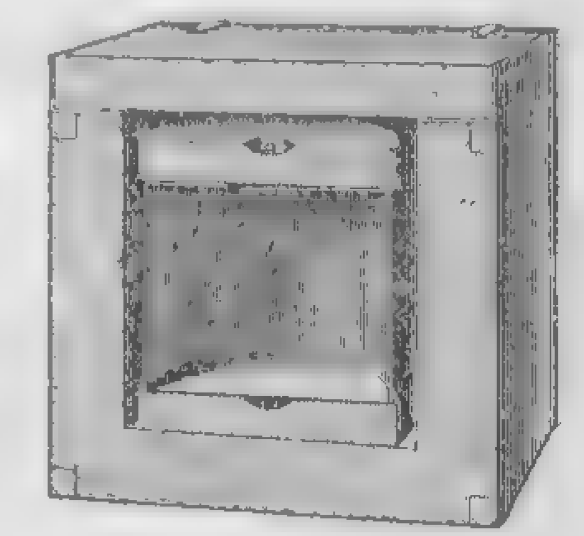


FIG. 192. A fireless cooker

3. With the aid of Fig. 192, which represents a fireless cooker, explain the principle on which fireless cooking is done.

4. Why will a moistened finger or the tongue freeze instantly to a piece of iron on a cold winter's day, but not to a piece of wood?

5. Why is the outer pail of an ice-cream freezer made of thick wood and the inner can of thin metal?

6. Does clothing ever afford us heat in winter? How, then, does it keep us warm?

7. In a steam-heating system why are the pipes that carry steam from the boiler to the radiators often covered with cellular asbestos? Why is the cellular structure an advantage?

CONVECTION

255. Convection in liquids. Although the conducting power of liquids is very small, as was shown in the experiment of § 251, yet they are able, under certain circumstances, to transmit heat much more effectively than are solids. Thus, if the ice in the experiment of Fig. 188 had been placed at the top and the

flame at the bottom, the ice would have been melted very quickly. This shows that heat is transferred very much more readily from the bottom of the tube toward the top than from the top toward the bottom. The mechanism of this heat transference will be evident from the following experiment:

Let a round-bottomed flask (Fig. 193) be half filled with water and a few crystals of magenta dropped into it. Then let the bottom of the flask be heated with a Bunsen burner. The magenta will reveal the fact that the heat sets up currents the direction of which is upward in the region immediately above the flame but downward at the sides of the vessel. It will not be long before the whole of the water is uniformly colored. This shows how thorough is the mixing accomplished by the heating.

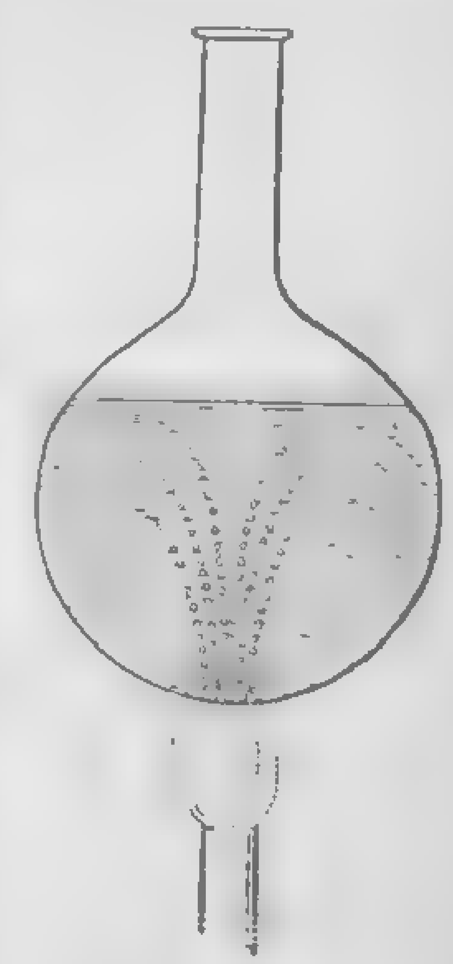


FIG. 193. Convection currents

The explanation of the phenomenon is as follows: The water nearest the flame became heated and expanded. It was thus rendered less dense than the surrounding water, and was accordingly forced to the top by the pressure transmitted from the colder and therefore denser water at the sides which then came in to take its place.

It is obvious that this method of heat transfer is applicable only to fluids. The essential difference between it and conduction is that the heat is not transferred from molecule to molecule throughout the whole mass, but rather is transferred by the bodily movement of comparatively large masses of the heated liquid from one point to another. This method of heat transference is known as *convection*.

256. Winds and ocean currents. Winds are convection currents in the atmosphere caused by unequal heating of the earth by the sun. Let us consider, for example, the land and sea breezes so familiar to all dwellers near the coasts of large bodies of water. During the daytime the land is heated more

rapidly than the sea, because the specific heat of water is much greater than that of earth. Hence the hot air over the land expands and is forced up by the colder and denser air over the sea which moves in to take its place. This constitutes the sea breeze, which blows during the daytime, usually reaching its maximum strength in the late afternoon. At night the earth cools more rapidly than the sea and hence the direction of the wind is reversed. The effect of these breezes is seldom felt more than twenty-five miles from shore.

Ocean currents are caused partly by the unequal heating of the sea and partly by the direction of the prevailing winds. In general, both winds and currents are so modified by the configuration of the continents that it is only over broad expanses of the ocean that the direction of either can be predicted from simple considerations.

RADIATION

257. A third method of heat transference. There are certain phenomena in connection with the transfer of heat for which conduction and convection are wholly unable to account. For example, if one sits in front of a hot grate fire, the heat which he feels cannot come from the fire by convection, because the currents of air are moving toward the fire rather than away from it. It cannot be due to conduction, because the conductivity of air is extremely small and the colder currents of air moving toward the fire would more than neutralize any transfer outward due to conduction. There must therefore be some way in which heat travels across the intervening space other than by conduction or convection.

This is still more evident when we consider the heat which comes to us from the sun. Conduction and convection take place only through the agency of matter; but we know that the space between the earth and the sun is not filled with ordinary matter, or else the earth would be retarded in its motion through space. *Radiation* is the name given to this

third method by which heat travels from one place to another, and which is illustrated in the passing of heat from a grate fire to a body in front of it, or from the sun to the earth.

258. The nature of radiation. The nature of radiation will be discussed more fully in Chapter XXI. It will be sufficient here to call attention to the following differences between conduction, convection, and radiation.

First, while conduction and convection are comparatively slow processes, the transfer of heat by radiation takes place with the enormous speed with which light travels, namely 186,000 miles per second. That the two speeds are the same is evident from the fact that at the time of an eclipse of the sun the shutting off of heat from the earth is observed to take place at the same time as the shutting off of light.

Secondly, radiant heat travels in straight lines, whereas conducted or convected heat may follow the most circuitous routes. The proof of this statement is found in the familiar fact that radiation may be cut off by means of a screen placed directly between a source and the body to be protected.

Thirdly, radiant heat may pass through a medium without heating it. This is shown by the fact that the upper regions of the atmosphere are very cold, even in the hottest days in summer, or that a hothouse may be much warmer than the glass through which the sun's rays enter it.

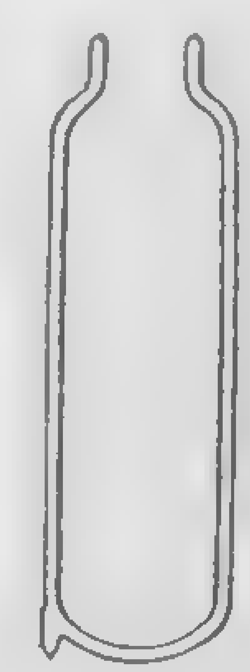


Fig. 194. The inner glass flask of a vacuum bottle

259. The Dewar flask and the vacuum bottle. For the retention of extremely cold liquids, such, for example, as liquefied air, whose boiling point is − 180° C., Dewar invented a double-walled vessel. The space between the walls is a vacuum, and the inner surface of the outer vessel and the outer surface of the inner vessel are silvered. There are three ways in which heat may pass inward through the double wall — conduction, convection, and radiation. The vacuum prevents almost entirely the first two, while the silvering

eliminates passage of heat by radiation. The well-known glass part of the vacuum bottle (Fig. 194) is simply a cylindrical Dewar flask for keeping liquids either hot or cold, since it is as difficult for heat to pass outward through the walls as to pass inward. The glass flask is provided with a cork stopper, and a strong outside metal case for its protection. Hot liquids, as well as those that are cold, may be kept for several hours in a vacuum bottle with only a few degrees change in temperature.

The Heating and Ventilating of Buildings

260. The principle of ventilation. The heating and ventilating of buildings are accomplished chiefly through the agency of convection.

To illustrate the principle of ventilation let a candle be lighted and placed in a vessel containing a layer of water (Fig. 195). When a lamp chimney is placed over the candle so that the bottom of the chimney is under the water, the flame will slowly die down and finally be extinguished. This is because the oxygen, which is essential to combustion, is gradually used up and no fresh supply is possible with the arrangement described. If the chimney is raised even a very little above the water, the dying flame will at once brighten. Why? If a metal or cardboard partition is inserted in the chimney, as in Fig. 195, the flame will burn continuously, even when the bottom of the chimney is under water. The reason will be clear if a piece of burning touch paper (blotting paper soaked in a solution of potassium nitrate and dried) is held over the chimney. The smoke will show the direction of the air currents. (If the chimney is a large one, in order that the first part of the experiment may succeed, it may be necessary to use two candles; for too small a heated area permits the formation of downward currents at the sides. A spiral tube $\frac{1}{4}$ inch in diameter made of glazed paper and lighted at the center may be used instead of touch paper.)

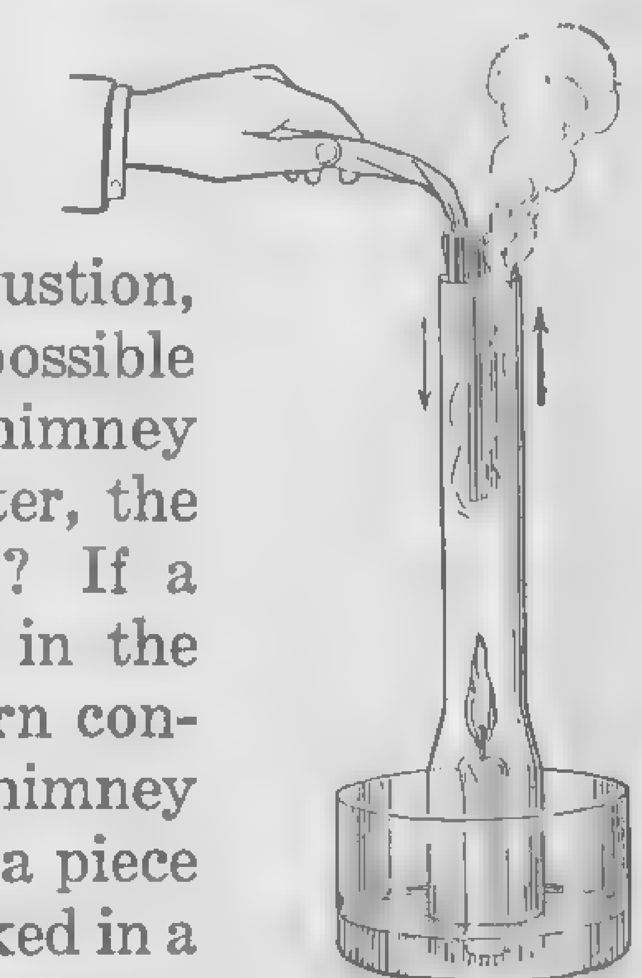


Fig. 195. Convection currents in air

261. Ventilation of houses. In order to secure satisfactory ventilation it is estimated that a room should be supplied with 2000 cubic feet of fresh air per hour for each occupant (a gas burner is equivalent in oxygen consumption to four persons). A current of air moving with a speed great enough to be just perceptible has a velocity of about 3 feet per second. Hence the area of opening required for each person when fresh air is entering at this speed is about 25 or 30 square inches. The manner of supplying this requisite amount of fresh air in dwelling houses depends upon the particular method of heating employed. (See opposite page 227.)

If a house is heated by stoves or fireplaces, no special provision for ventilation is needed. The foul air is forced up the chimney with the smoke by the entrance of the fresh air coming in through cracks about the doors and windows and through the walls, if highly porous.

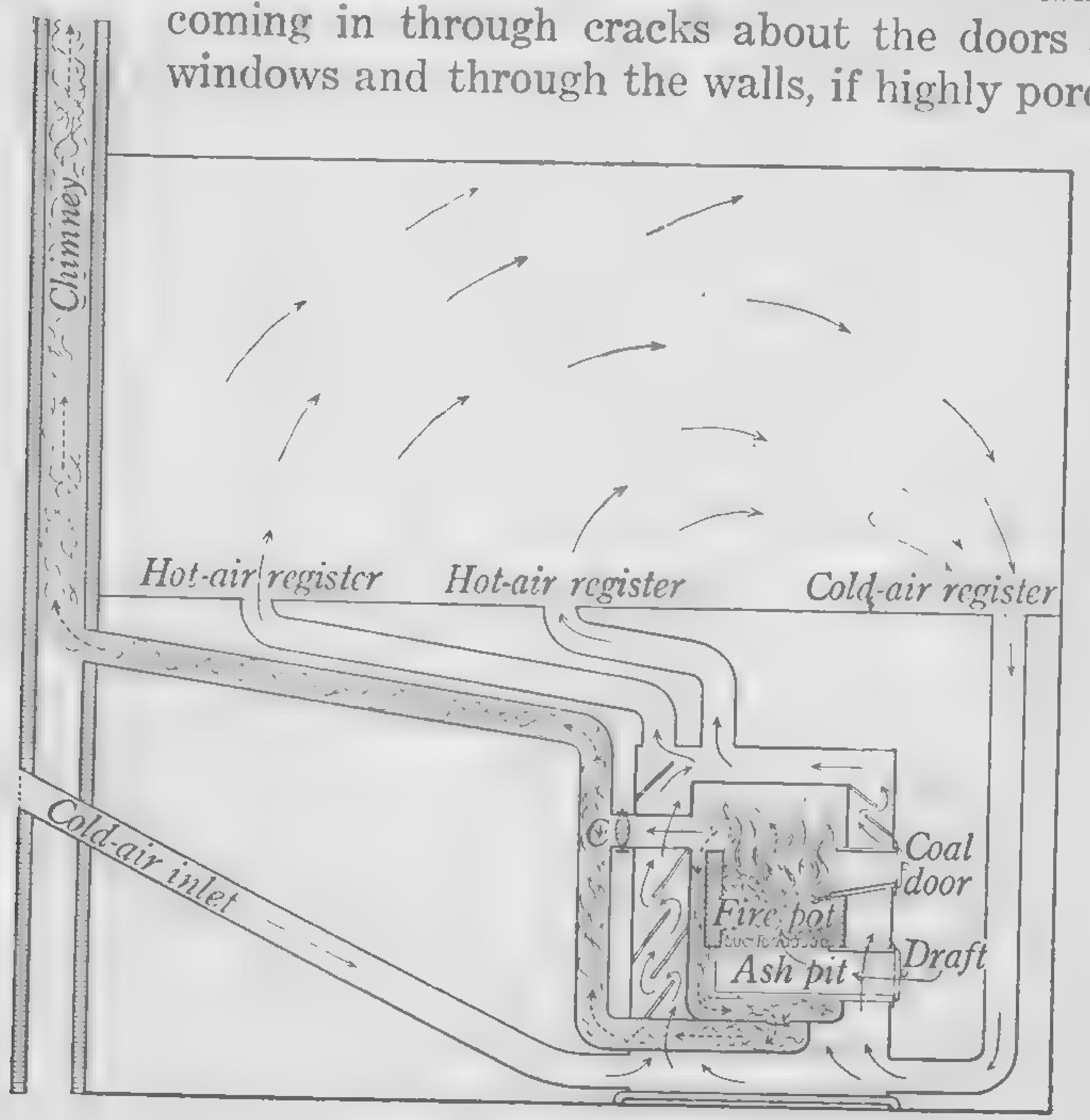
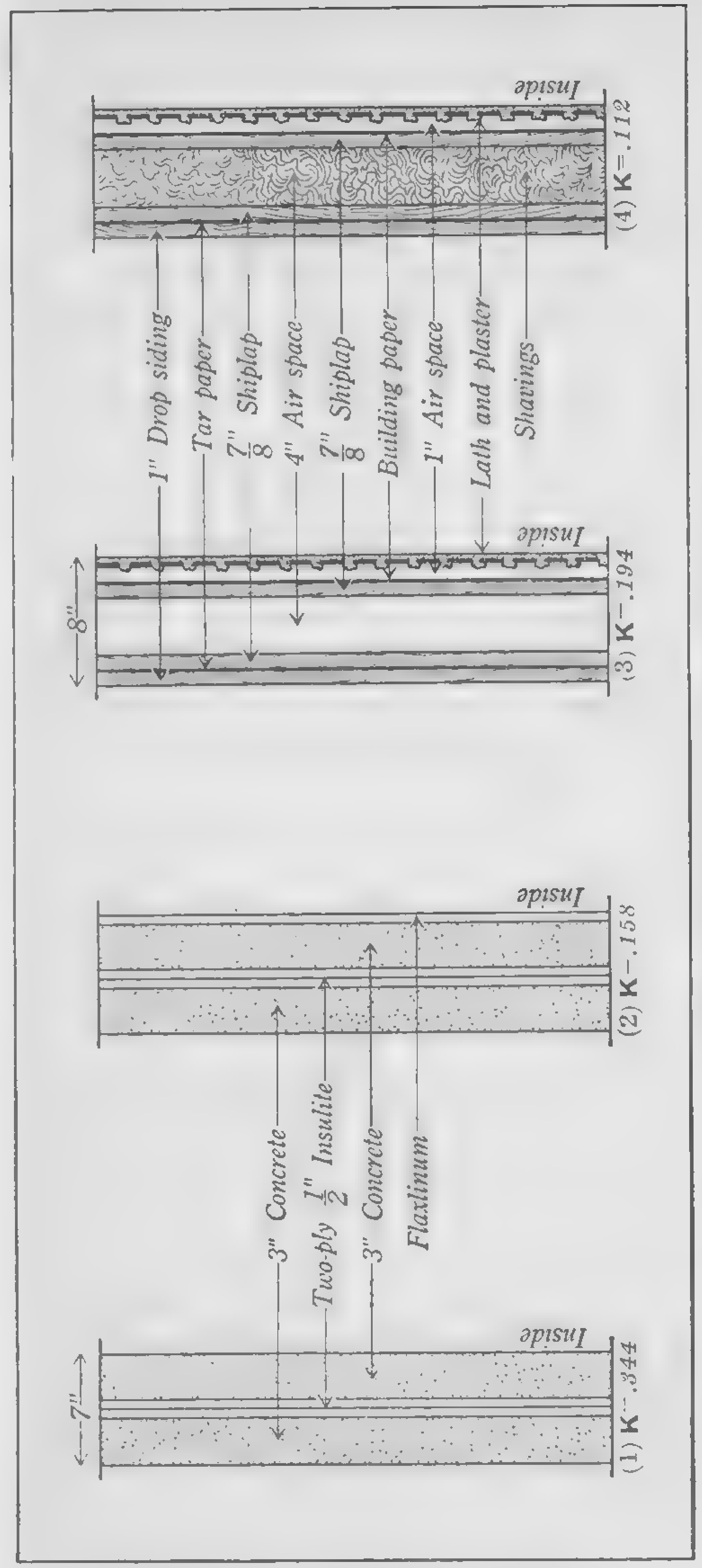
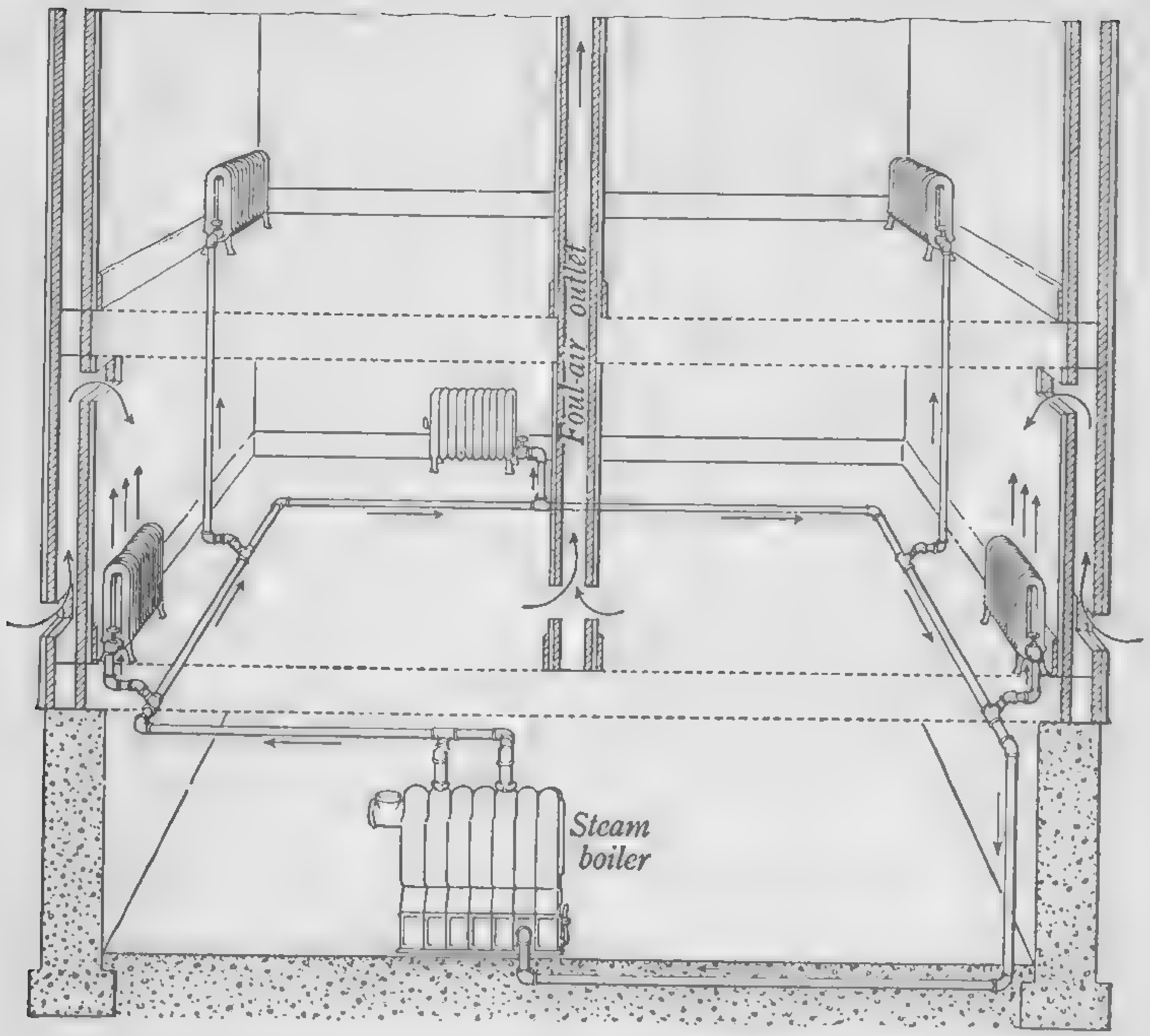


FIG. 196. Hot-air heating



HEAT INSULATION OF DWELLINGS

It is estimated that an annual saving of at least $100,000,000 in fuel in the United States alone would be made if the walls of houses were properly constructed with respect to heat insulation. Such walls not only conserve heat in cold climates, but exclude it from houses in warm climates. The facts given on this page are the results of tests recently made at the University of Saskatchewan (with the aid of little windowless experimental houses) upon the thermal conductivities of the various walls shown. **K** is proportional to thermal conductivity, and in the units used the value of **K** for a solid concrete wall 7 inches thick was .782. It will be seen from the values of **K** that walls (2) and (4), although costing not appreciably more than (1) and (3) respectively, require about half the fuel to maintain the temperature constant. Taking the thermal conductivity of solid concrete as the base of comparison, we find the loss through (1) was 44 per cent of the loss through solid concrete; through (2), 20 per cent; through (3), 25 per cent; through (4), 14 per cent



A STEAM-HEATING AND VENTILATING SYSTEM FOR A DWELLING

The diagram shows a simple steam-heating plant having a one-pipe circuit. Steam passes from the top of the boiler into a pipe which at all points slopes slightly downward throughout the entire circuit. Through branch pipes steam rises to the individual radiators, where it condenses and returns to the overhead pipe in the cellar and thence to the lower part of the boiler. Since the returning water occupies a volume approximately $\frac{1}{1600}$ of that of steam, it is obvious that a single pipe leading to each radiator is sufficient to carry both the outgoing steam and the returning water. Adequate ventilation of a steam-heated building may be secured, as shown in the figure, by providing openings in the walls immediately above the radiators through which fresh air may enter. The rising warm air from the radiators prevents the cold air from settling to the floor. The foul air of the room passes through openings located near the floor on another side of the room and thence upward through ventilating flues leading to the top of the house. This arrangement is shown in the lower story of the diagram

262. Hot-air heating. In houses heated by hot-air furnaces an air duct is usually supplied for the entrance of fresh cold air, in the manner shown in Fig. 196 (see "cold air inlet"). This cold air from outdoors is heated by passing in a circuitous way, as shown by the arrows, over the outer jacket of iron which covers the fire box. It is then delivered to the rooms. Here a part of it escapes through windows and doors, and the rest returns through the cold-air register to be reheated, after being mixed with a fresh supply from outdoors.

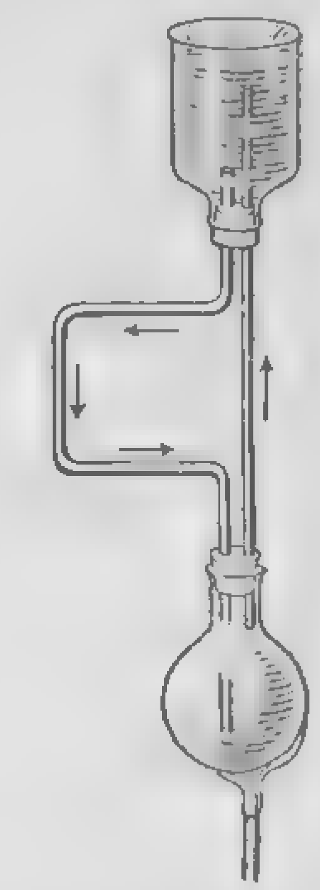


FIG. 197. Principle of hot-water heating

When the fire is first started, in order to gain a strong draft the damper C is opened so that the smoke may pass directly up the chimney. After the fire is under way, the damper C is closed so that the smoke and hot gases from the furnace must pass, as indicated by the dotted arrows, over a roundabout path, in the course of which they give up the major part of their heat to the steel walls of the jacket, which in turn pass it on to the air which is on its way to the living rooms.

263. Hot-water and steam heating. To illustrate the principle of hot-water heating let the arrangement shown in Fig. 197 be set up, the upper vessel being filled with colored water, and then let a flame be applied to the lower vessel. The colored water will show that the current moves in the direction of the arrows.

This same principle is involved in the gas-heating coil used in connection with the kitchen boiler (Fig. 198). Heat from the flame passes through the copper coil to the water, and convection begins as indicated by the arrows. When hot water is drawn from the top of the boiler, cold water enters near the bottom so as not to mingle with the hot water that is being

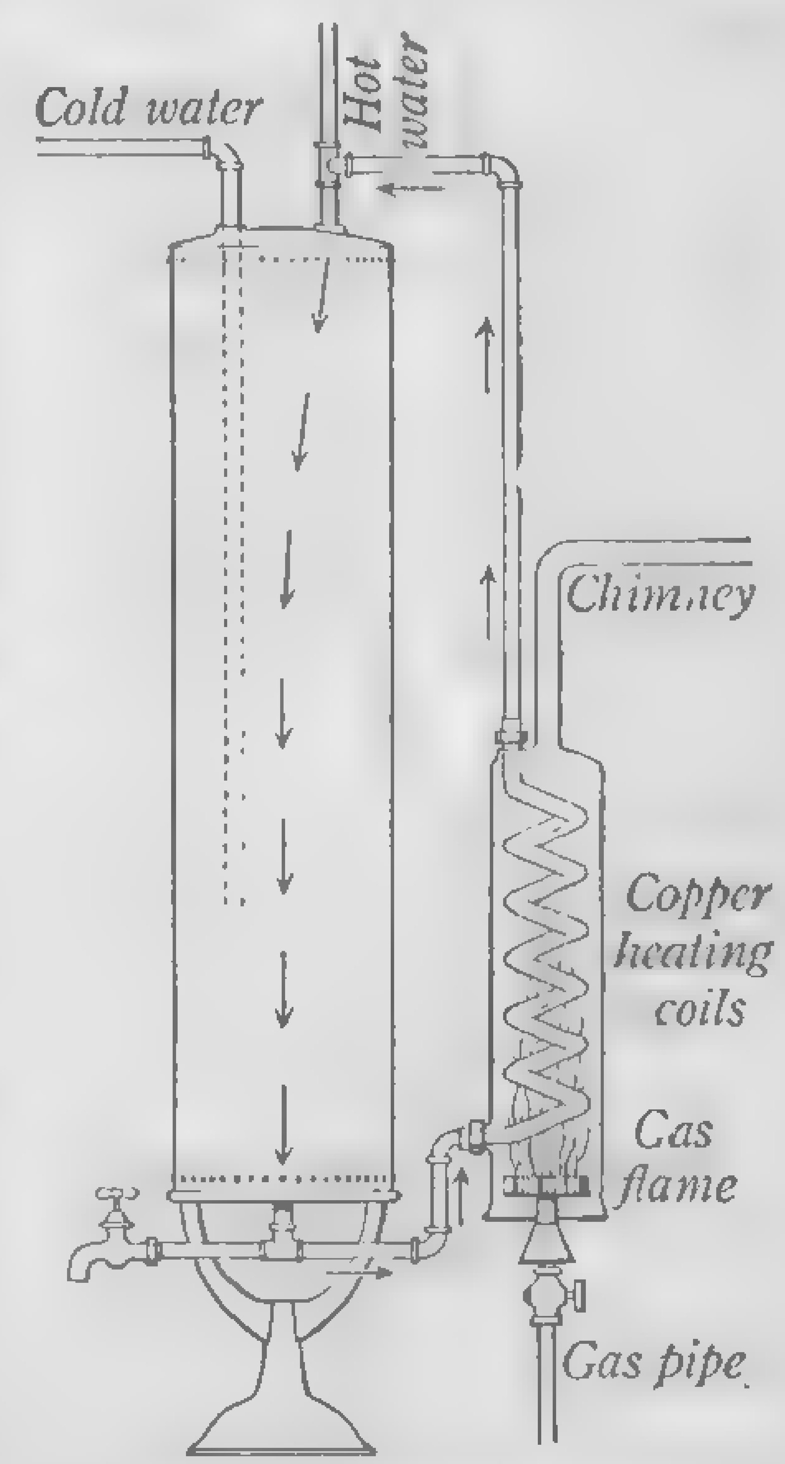


FIG. 198. A gas-heating coil

used. The principle is still further illustrated by the cooling systems used for keeping automobile engines from becoming overheated. Heat passes from the engine into the water, which loses heat in circulating through the coils of the radiator (see opposite page 210).

The actual arrangement of boiler and radiators in one system of hot-water heating is shown in Fig. 199. The water heated in the furnace rises directly through the pipe A to a radiator R, and returns again to the bottom of the furnace through the pipes B and D. The circulation is maintained because the column of water in A is hotter and therefore possesses less density than the water in the return pipe B.

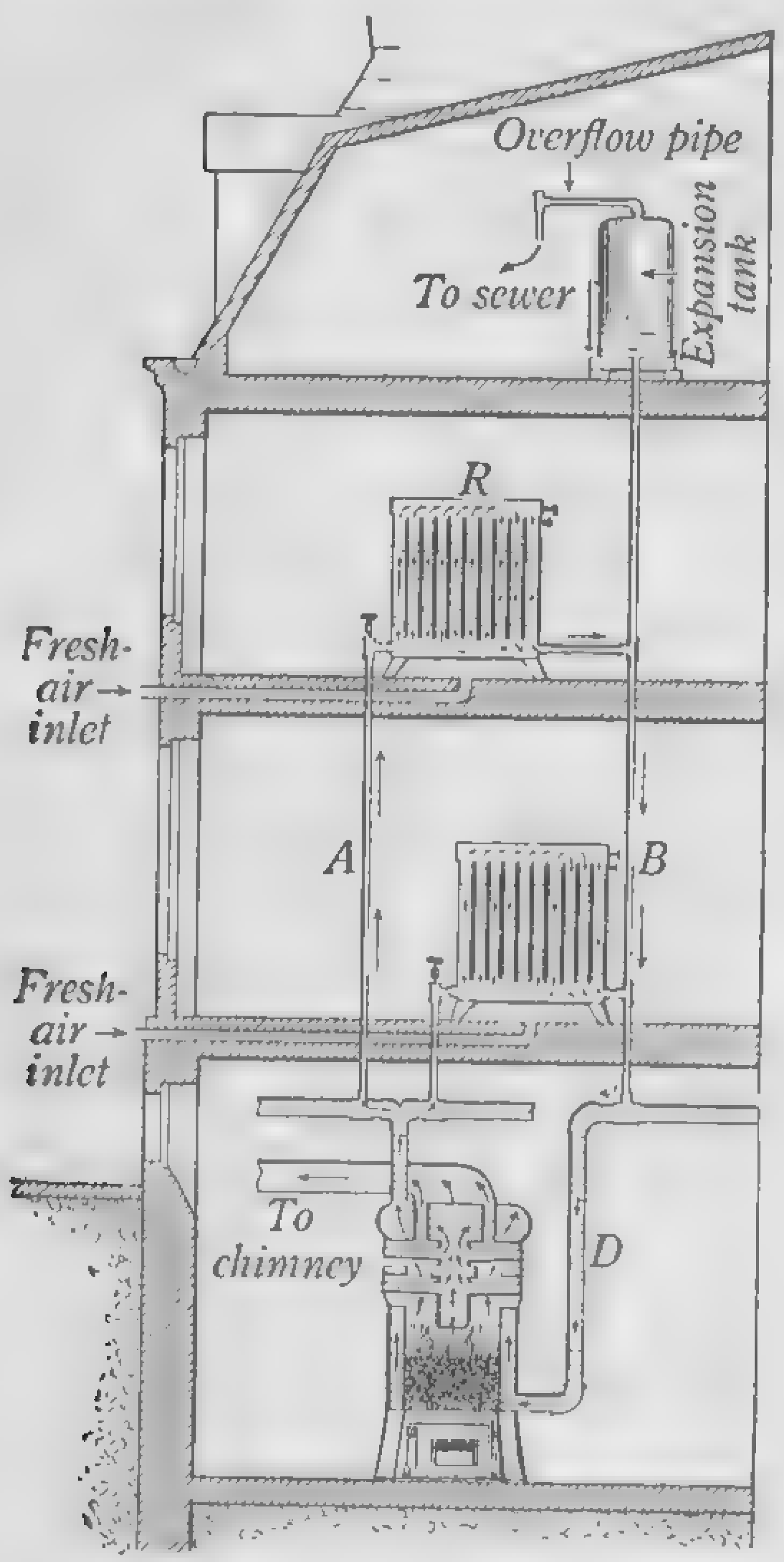


FIG. 199. Hot-water heater

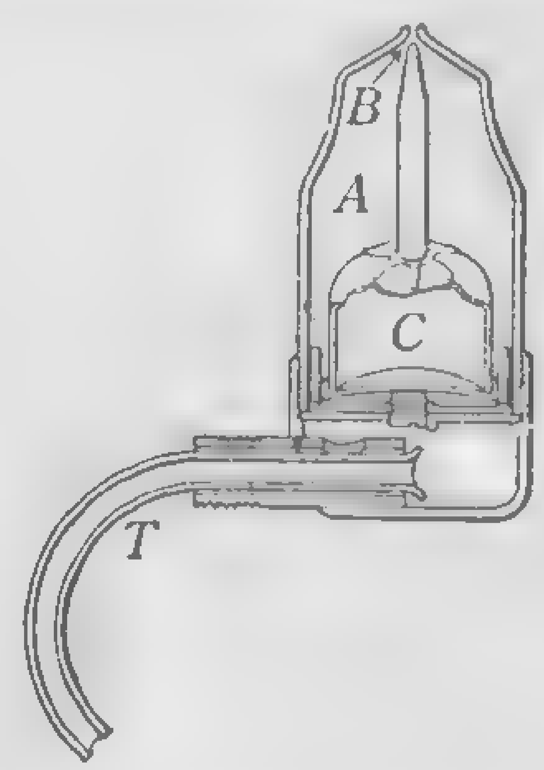


FIG. 200. A radiator air valve

By eliminating the expansion tank and partly filling the boiler with water the system could be converted into a steam-heating plant (see opposite page 227).

Air valves (Fig. 200) are placed on steam radiators to allow air within the radiator to pass out ahead of the on-coming steam. Air escapes from the small hole B, and any water which enters the valve runs back into the radiator through the tube T. When the hot steam reaches the form of valve shown in Fig. 200, the vaporization of a volatile liquid (ethyl chloride) in the closed capsule C (shown partly cut away) bulges the curved bottom downward so that the capsule and pin A rise, closing the hole B.

SUMMARY. Convection is the transfer of heat energy through the rising of heated portions of fluids and the falling of colder and hence denser portions.

Radiation is the transfer through space, with the speed of light, of energy that appears as heat upon absorption by matter.

Heat radiations produce very little effect when they strike a polished silver surface, for they are almost wholly reflected.

Ventilation, hot-air heating, and hot-water heating are applications of convection.

In steam heating every gram of steam that condenses in the radiators liberates 539 calories.

QUESTIONS AND PROBLEMS*

1. In what way do your hands receive heat from a hot radiator when you touch it? when you hold your hands at the side of it (not touching it)? when you hold your hands a little above the radiator?

2. Explain the efficiency of a vacuum bottle.

3. In a system of hot-water heating why does the return pipe always connect at the bottom of the boiler, while the outgoing pipe connects with the top?

4. If we attempt to start a fire in the kitchen range when the chimney is cold, the range "smokes." Explain.

5. Explain the cause of the sea breeze which occurs in coast regions on summer afternoons.

6. Why is it that a hollow wall filled with sawdust is a better nonconductor of heat than the same wall filled with air alone?

7. When a room is heated by a fireplace, which of the three methods of heat transference plays the most important rôle?

8. During a period of one hour 4 kg. of steam at 100° C. condensed in a radiator and the temperature of the resulting water as it left the radiator was 92° C. How many calories of heat per second were made available during this time for heating the room?

* Supplementary questions and problems for Chapter XI are given in the Appendix.

CHAPTER XII

MAGNETISM *

General Properties of Magnets

264. Magnets. It has been known for many centuries that some specimens of the ore known as magnetite (Fe_3O_4) have the property of attracting small bits of iron and steel. This ore probably received its name from the fact that it was first observed in the province of Magnesia, in Thessaly. Pieces of this ore which exhibit this attractive property are known as *natural magnets.*

It was also known to the ancients that artificial magnets may be made by stroking pieces of steel with natural magnets, but it was not until about the twelfth century that the discovery was made that *a suspended magnet will assume a north-and-south position.* Because of this latter property natural magnets became known as lodestones (leading stones), and magnets, either artificial or natural, began to be used for determining directions. The first mention of the use of the compass in Europe is in 1190. It is thought to have been introduced from China. (See opposite page 239 for the gyrocompass.)

Magnets are now made either by stroking bars of steel in one direction with a magnet or by passing electric currents about the bars in a manner to be described later. The form shown in Fig. 201 is called a *bar magnet,* and the one shown in Fig. 202 a *horseshoe magnet.* The latter form is the more common and is the better form for lifting.

* This chapter should be either accompanied or preceded by laboratory experiments on magnetic fields and on the molecular nature of magnetism. See, for example, Experiments 31 and 32 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

If a magnet is dipped into iron filings, the filings will be seen to cling in tufts near the ends but scarcely at all near the middle (Fig. 203). These places near the ends of a magnet at which its strength seems to be concentrated are called the *poles* of the magnet. The end of a freely swinging magnet which points to the north is designated as the north-seeking pole or simply the *north pole* (N); the other end is designated as the south-seeking pole or the *south pole* (S). *The direction in which a compass needle points is called the magnetic meridian.*

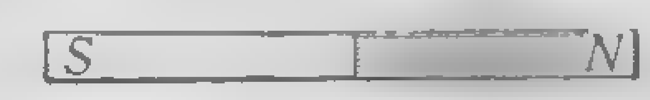


Fig. 201. A bar magnet

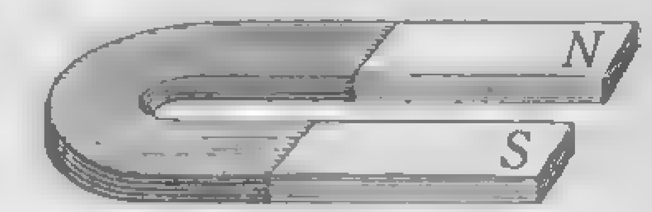


Fig. 202. A horseshoe magnet

265. Laws of magnetic attraction and repulsion. In the experiment with the iron filings no particular difference was observed between the action of the two poles. That there is a difference, however, may be shown by experimenting with two magnets, either of which may be suspended (Fig. 204). If two N poles are brought near each other, they are found to repel each other. The S poles likewise are found to repel each other. But the N pole of one magnet is found to be attracted by the S pole of another. The results of these experiments may be summarized in a general law: *Magnet poles of like kind repel each other, and poles of unlike kind attract each other.*

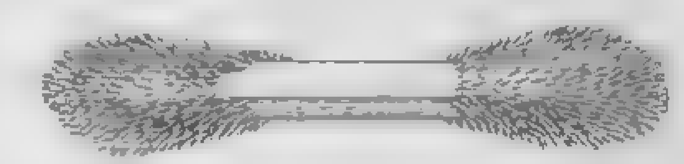


Fig. 203. Iron filings clinging to a bar magnet

The force which any two poles exert upon each other in air is equal to the product of the pole strengths divided by the square of the distance between them.

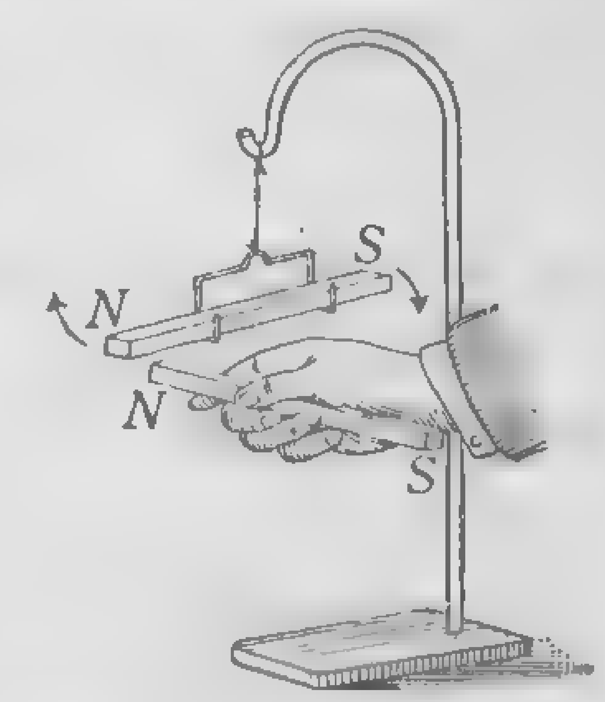


Fig. 204. Magnetic attractions and repulsions

A unit pole is defined as a pole which, when placed at a distance of 1 centimeter from an exactly equal and similar pole, in air, repels it with a force of 1 dyne.

266. Magnetic materials. Iron and steel are the only substances that exhibit magnetic properties to any marked degree. Nickel and cobalt are also attracted appreciably by strong magnets. Bismuth, antimony, and a number of other substances are actually repelled instead of attracted, but the effect is very small. It has recently been found possible to make strongly magnetic alloys out of certain nonmagnetic materials. For example, a mixture of 65 per cent copper, 27 per cent manganese, and 8 per cent aluminum is strongly magnetic. These are called Heusler alloys. For practical purposes, however, iron and steel may be considered as the only magnetic materials.

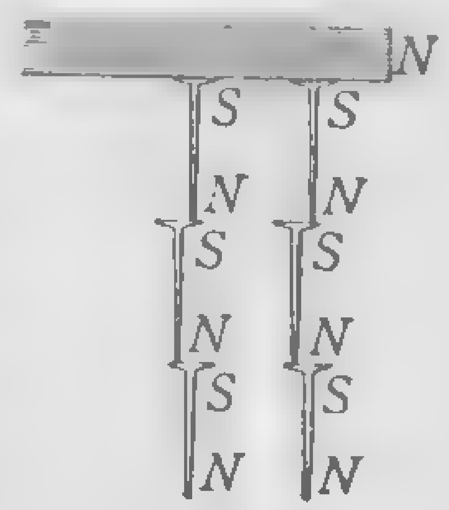


FIG. 205. Magnetism induced by contact

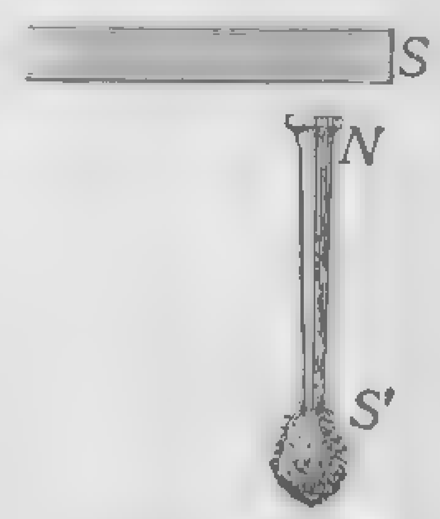


FIG. 206. Magnetism induced without contact

267. Magnetic induction. If a small unmagnetized nail is suspended from one end of a bar magnet, it is found that a second nail may be suspended from this first nail (which itself acts like a magnet), a third from the second, and so on, as shown in Fig. 205; but if the bar magnet is carefully pulled away from the first nail, the others will instantly fall away from each other, thus showing that the nails were strong magnets only so long as they were in contact with the bar magnet. Any piece of soft iron may be thus magnetized *temporarily* by holding it in contact with a permanent magnet. Indeed, it is not necessary that there be actual contact, for if a nail is simply brought near to the permanent magnet it is found to become a magnet. This may be proved by presenting some iron filings to one end of a nail held near a magnet in the manner shown in Fig. 206. Even inserting a plate of glass, or of copper, or of any other material except iron between S and N will not change appreciably the number of filings which cling to the end of S', a fact which shows that *nonmagnetic materials are transparent to magnetic forces*; but

as soon as the permanent magnet is removed, most of the filings will fall. *Magnetism produced by the mere presence of adjacent magnets, with or without contact, is called induced magnetism.* If the induced magnetism of the nail in Fig. 206 is tested with a compass needle, it is found that the *remote* induced pole is of the same kind as the inducing pole, and that the *near* pole is of unlike kind. This is the general law of magnetic induction.

Magnetic induction explains the fact that a magnet attracts an unmagnetized piece of iron, for it first magnetizes it by induction, so that the near pole is unlike the inducing pole, and the remote pole like the inducing pole; and then, since the two unlike poles are closer together than the like poles, the attraction overbalances the repulsion, and the iron is drawn toward the magnet. Magnetic induction also explains the formation of the tufts of iron filings shown in Fig. 203, each little filing becoming a temporary magnet such that the end pointing toward the inducing pole is unlike this pole, and the end pointing away from it is like this pole. The bush-like appearance is due to the repelling action which the outside free poles exert upon each other.

268. Retentivity and permeability. A piece of soft iron will very easily become a strong temporary magnet, but when removed from the influence of the magnet it loses practically all its magnetism. On the other hand, a piece of steel will not be so strongly magnetized as the soft iron, but it will retain a much larger fraction of its magnetism after it is removed from the influence of the permanent magnet. This quality of resisting either magnetization or demagnetization is called *retentivity*. Thus steel has a much greater retentivity than wrought iron, and, in general, the harder the steel the greater its retentivity.

A substance having the property of becoming strongly magnetic under the influence of a permanent magnet, whether it has a high retentivity or not, is said to possess *permeability* in large degree. Thus iron is much more permeable than nickel,

but for weak fields a new compound of iron and nickel called *permalloy* has thirty times the permeability of soft iron.

269. Magnetic lines of force. If we could separate the *N* and *S* poles of a small magnet so as to get an independent *N* pole, and if we were to place this *N* pole near the *N* pole of a bar magnet, it would move over to the *S* pole along some curved path similar to that shown in Fig. 207. The reason it would move in a curved path is that it would be simultaneously repelled by the *N* pole of the bar magnet and attracted by its *S* pole, and the relative strengths of the attraction and the repulsion would continually change as the relative distances of the moving pole from these two poles changed.

FIG. 207. A line of force set up by the magnet *AB*

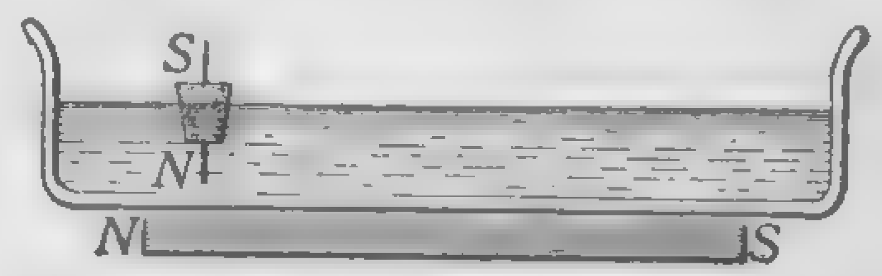


FIG. 208. Showing direction of motion of an isolated pole near a magnet

To verify this conclusion let a strongly magnetized sewing needle be floated in a small cork in a shallow dish of water, and let a bar or a horseshoe magnet be placed just above the dish or just beneath it (see Fig. 208). The cork and the needle will then move as would an independent pole, since the remote pole of the needle is so much farther from the magnet than the near pole that its influence on the motion is very small. The cork will actually be found to move in a curved path from *N* to *S*.

Any path which an independent *N* pole would take in going from *N* to *S* is called a *line of force.* The simplest way of finding the direction of this path at any point near a magnet is to hold a short compass needle at the point considered. The needle sets itself along the line in which its poles would move if independent; that is, along the line of force which passes through the given point (see *C*, Fig. 207).

270. Fields of force. The region about a magnet in which its magnetic forces can be detected is called its *field of force.*

The easiest way of gaining an idea of the way in which the lines of force are arranged in the magnetic field about any magnet is to sift iron filings upon a piece of paper placed immediately over the magnet. Each little filing becomes a

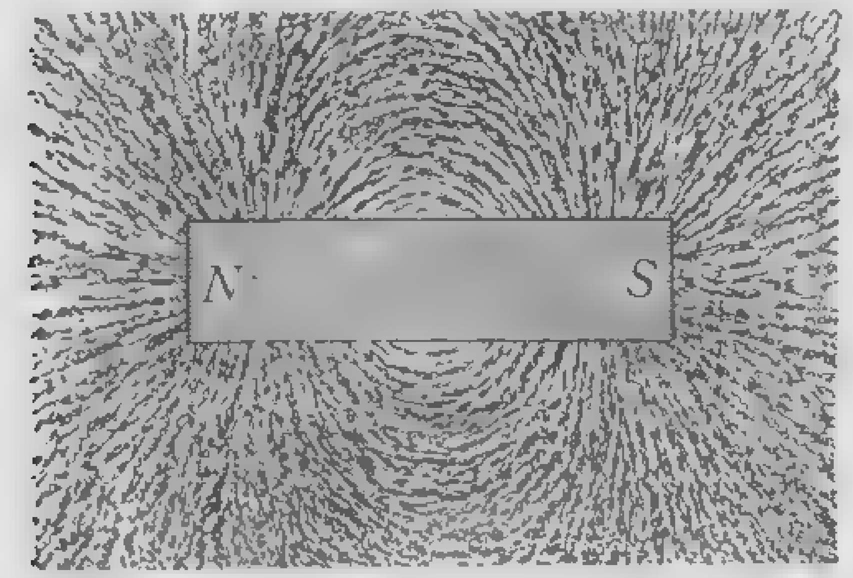


FIG. 209. Arrangement of iron filings about a bar magnet

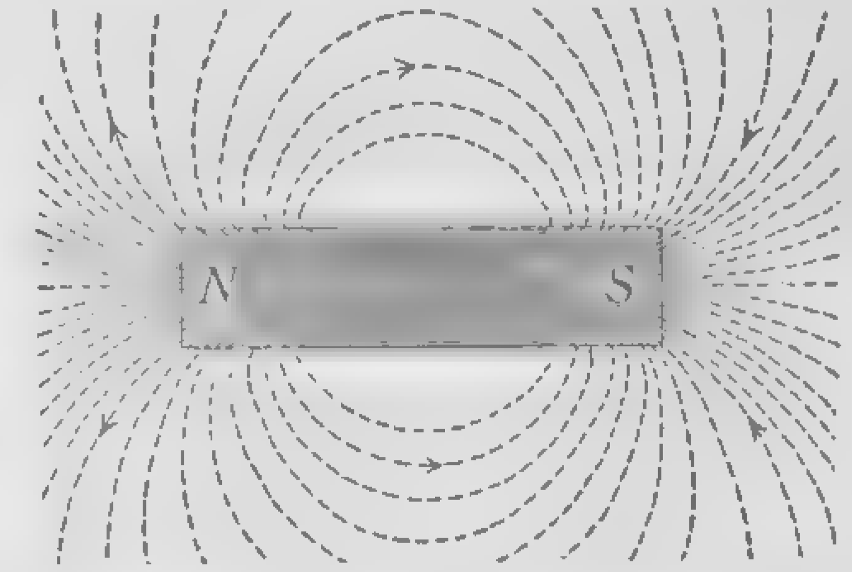


FIG. 210. Ideal diagram of field of a bar magnet

temporary magnet by induction, and therefore, like the compass needle, sets itself in the direction of the line of force at the point where it is. Fig. 209 shows how the filings arrange themselves about a bar magnet. Fig. 210 is the corresponding ideal diagram showing the lines of force emerging from the

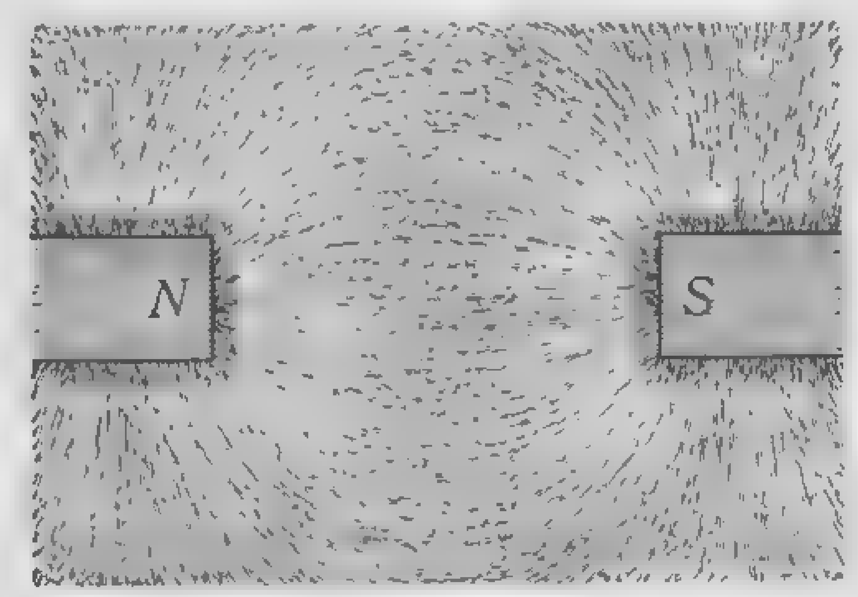


FIG. 211. Iron filings between unlike poles

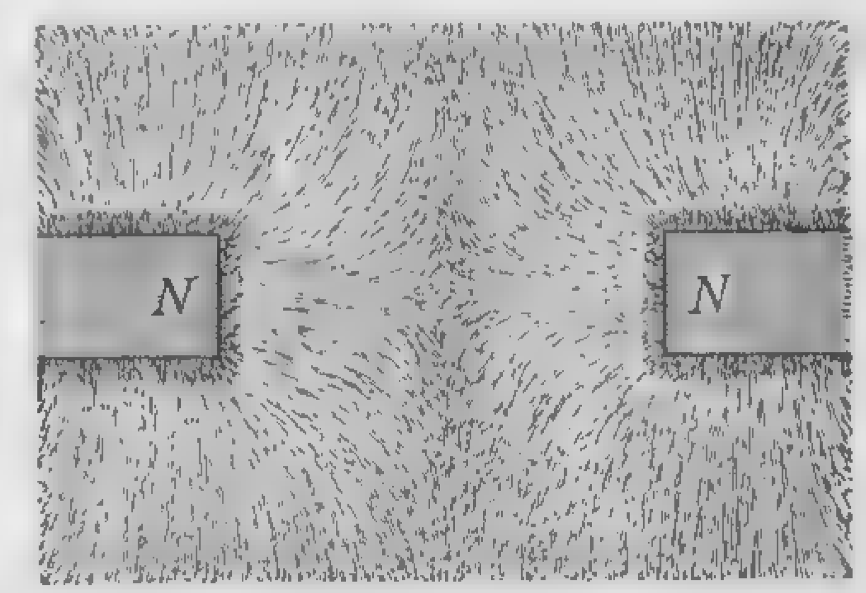


FIG. 212. Iron filings between like poles

N pole and passing about in curved paths to the *S* pole. It is customary to imagine these lines as returning through the magnet from *S* to *N* in the manner shown, so that each line is thought of as a closed curve. This convention was introduced by Faraday, and has been found of great assistance in correlating the facts of magnetism. Figs. 211 and 212 show

the arrangement of iron filings (1) between unlike poles and (2) between like poles.

A magnetic field of unit strength is defined as a field in which a unit magnet pole experiences 1 dyne of force. It is customary to represent graphically such a field by drawing one line per square centimeter through a surface such as $ABCD$ (Fig. 213) taken at right angles to the lines of force. If a unit N pole between N and S (Fig. 213) were pushed by the magnetic field toward S with a force of 1000 dynes, the strength of the field would be 1000 units, and it would be represented by 1000 lines per square centimeter.

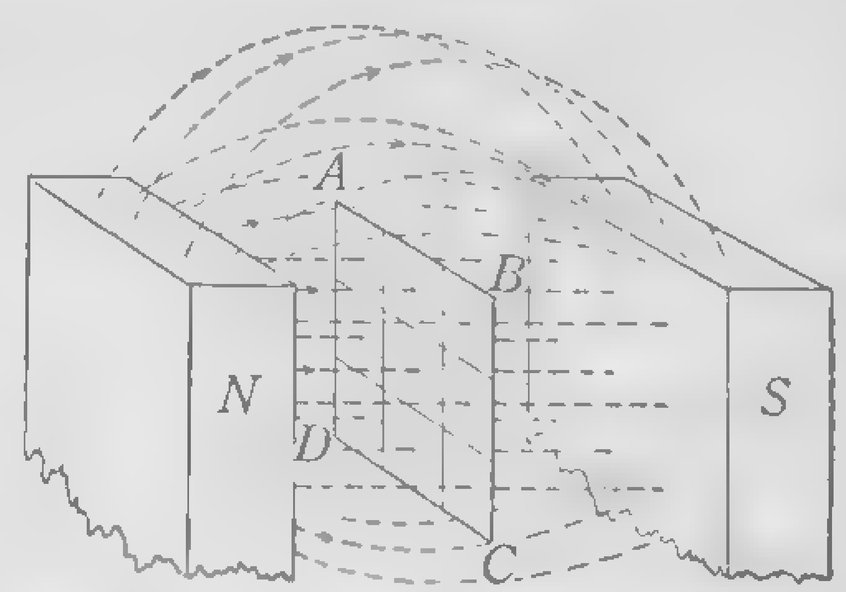


FIG. 213. The strength of a magnetic field is represented by the number of lines of force per square centimeter

271. Nature of magnetism. If a small test tube full of iron filings be stroked from end to end with a magnet, it will be found to have become itself a magnet; but it will lose its magnetism as soon as the filings are shaken up. If a magnetized knitting needle is heated red-hot, it will be found to have lost its magnetism completely. Again, if such a needle is jarred or hammered or twisted, the strength of its poles, as measured by their ability to pick up tacks or iron filings, will be found to be greatly diminished.

These facts point to the conclusion that magnetism has something to do with the arrangement of the atoms, molecules, or small molecular aggregates, since causes which violently disturb the particles within a magnet weaken its magnetism. Again, if a magnetized needle is broken, each part will be found to be a complete magnet; that is, two new poles will appear at the point of breaking: a new N pole on the part which has the original S pole, and a new S pole on the part which has the original N pole. The subdivision may be continued indefinitely, but always with the same result, as indicated in Fig. 214. This suggests that some very small

particles within a magnetized bar may themselves be little magnets arranged in rows with their opposite poles in contact.

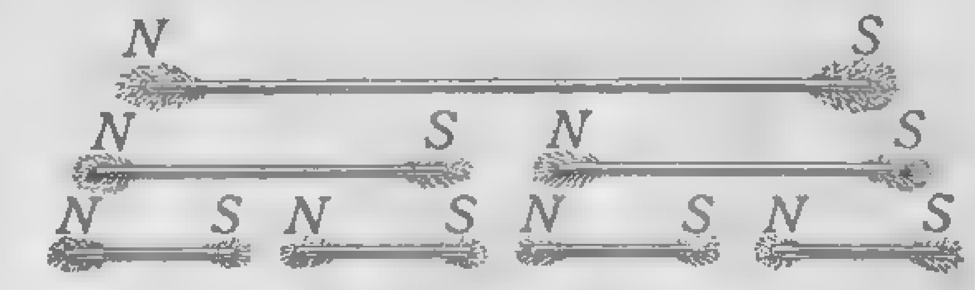


FIG. 214. Effect of breaking a magnet

If an unmagnetized piece of hard steel is pounded vigorously while it lies between the poles of a magnet, or if it is heated to redness and then allowed to cool in this position, it will be found to have become magnetized. This suggests that some very small particles within the steel are magnets even when the bar as a whole is not magnetized, and that magnetization may consist in causing them to arrange themselves in rows, end to end, just as the magnetization of the tube of iron filings mentioned above was due to a special arrangement of the filings.

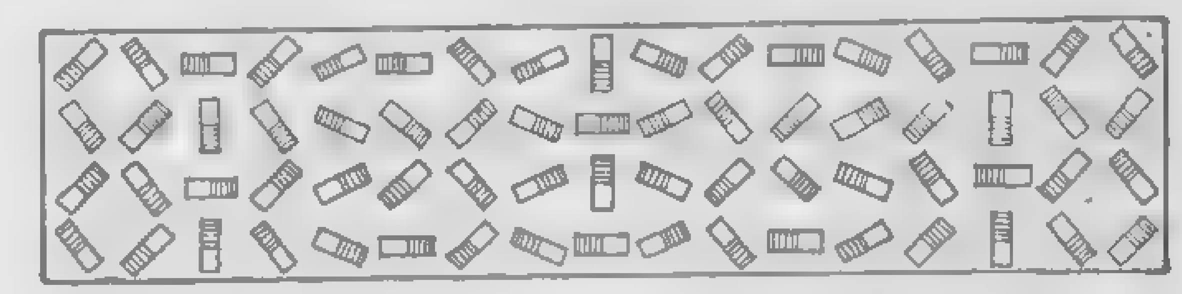


FIG. 215. Arrangement of particles in an unmagnetized iron bar

272. Theory of magnetism. In an unmagnetized bar of iron or steel it is probable, then, that some very small particles within the bar are tiny magnets which are arranged either haphazard or in little closed groups or chains, as in Fig. 215, so that, on the whole, opposite poles neutralize each other throughout the bar. But when the bar is brought near a magnet, these particles are swung around by the outside magnetic force into an arrangement somewhat like the one shown in Fig. 216, where the opposite poles completely neutralize each other only in the middle of the bar. According to this view, heating and jarring weaken the magnet, because they tend to shake the particles

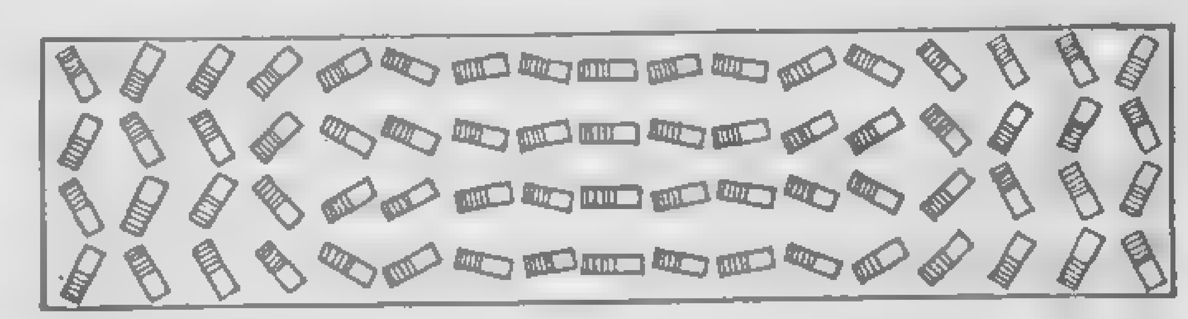


FIG. 216. Arrangement of particles in a magnetized iron bar

out of alignment. On the other hand, heating and jarring facilitate magnetization when the bar is between the poles of a magnet, because they assist the magnetizing force in breaking up closed magnetic groups and chains and getting the individual tiny magnets into alignment. Soft iron has higher permeability than hard steel, because the particles of the former substance are much easier to swing into alignment than those of the latter substance. Steel has a very much greater retentivity than soft iron, because its particles are not so easily moved out of position when once they have been aligned.

273. Saturation. Strong evidence for the correctness of the preceding view is found in the fact that a piece of iron or steel cannot be magnetized beyond a certain limit, no matter how strong the magnetizing force is. This limit probably corresponds to the condition in which the axes of all the tiny magnets are brought into parallelism, as in Fig. 217. The magnet is then said to be *saturated*, since it is as strong as it is possible to make it.

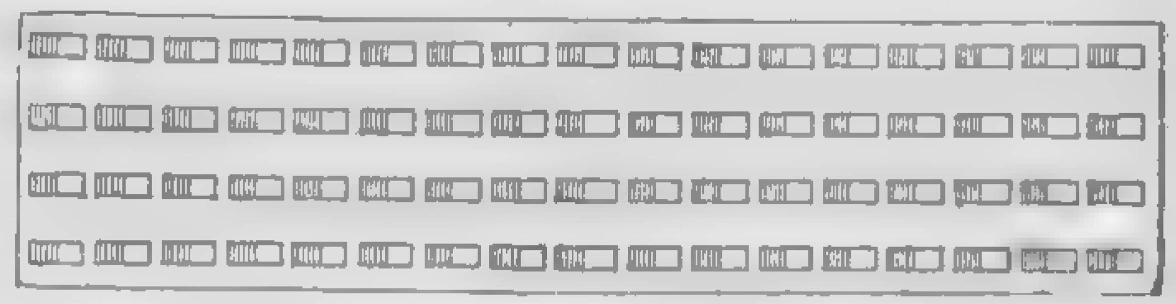


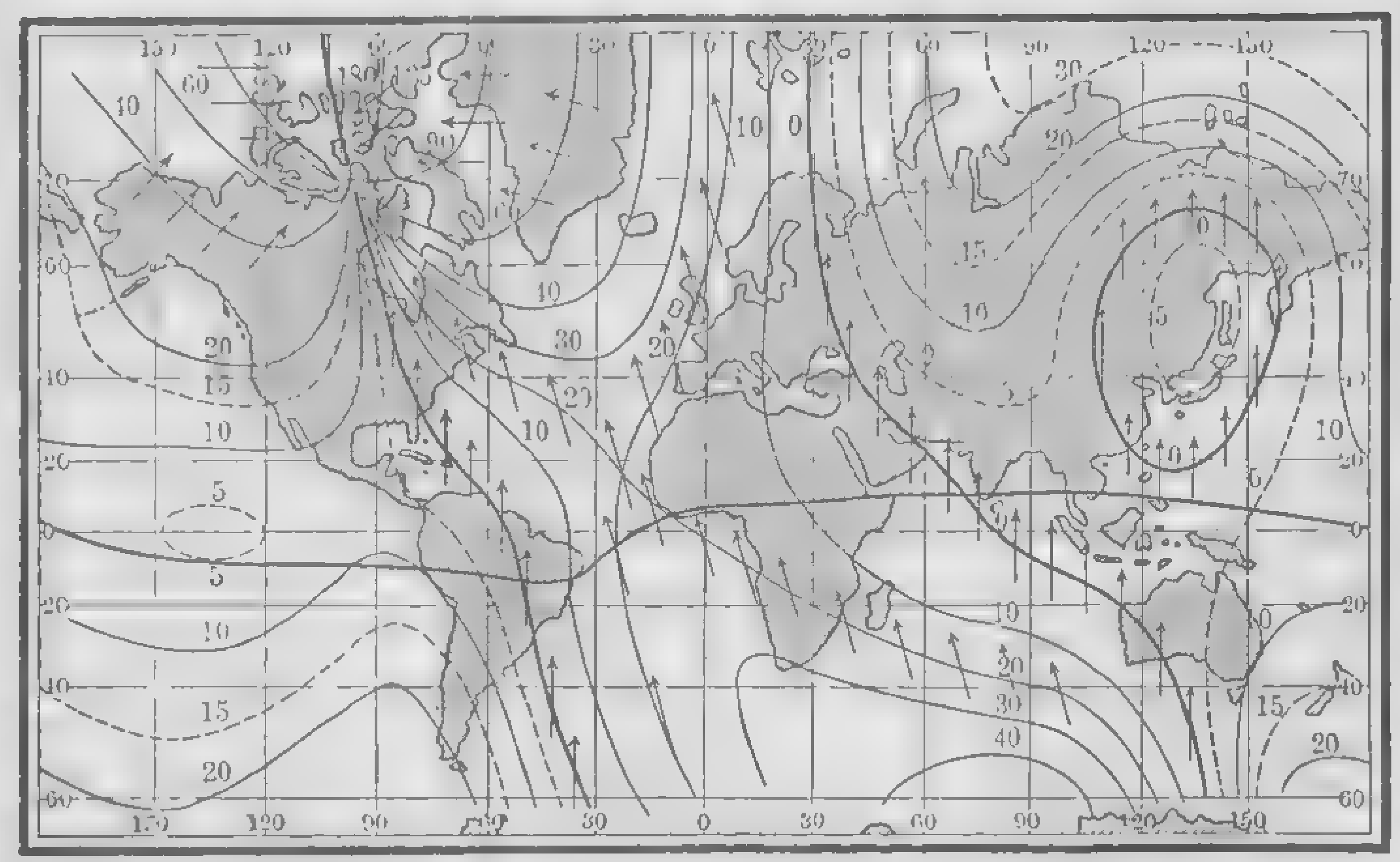
FIG. 217. Arrangement of particles in a saturated magnet

TERRESTRIAL MAGNETISM

274. The earth's magnetism. The fact that a compass needle points north and south, or approximately so, indicates that the earth itself is a great magnet having an S pole near the geographic north pole and an N pole near the geographic south pole; for the magnetic pole of the earth near the geographic north pole must of course be unlike the pole of a suspended magnet which points toward it, and the pole of the suspended magnet which points toward the north is the one which, by convention, it has been decided to call the N pole. The magnetic pole of the earth which is near the north geo-

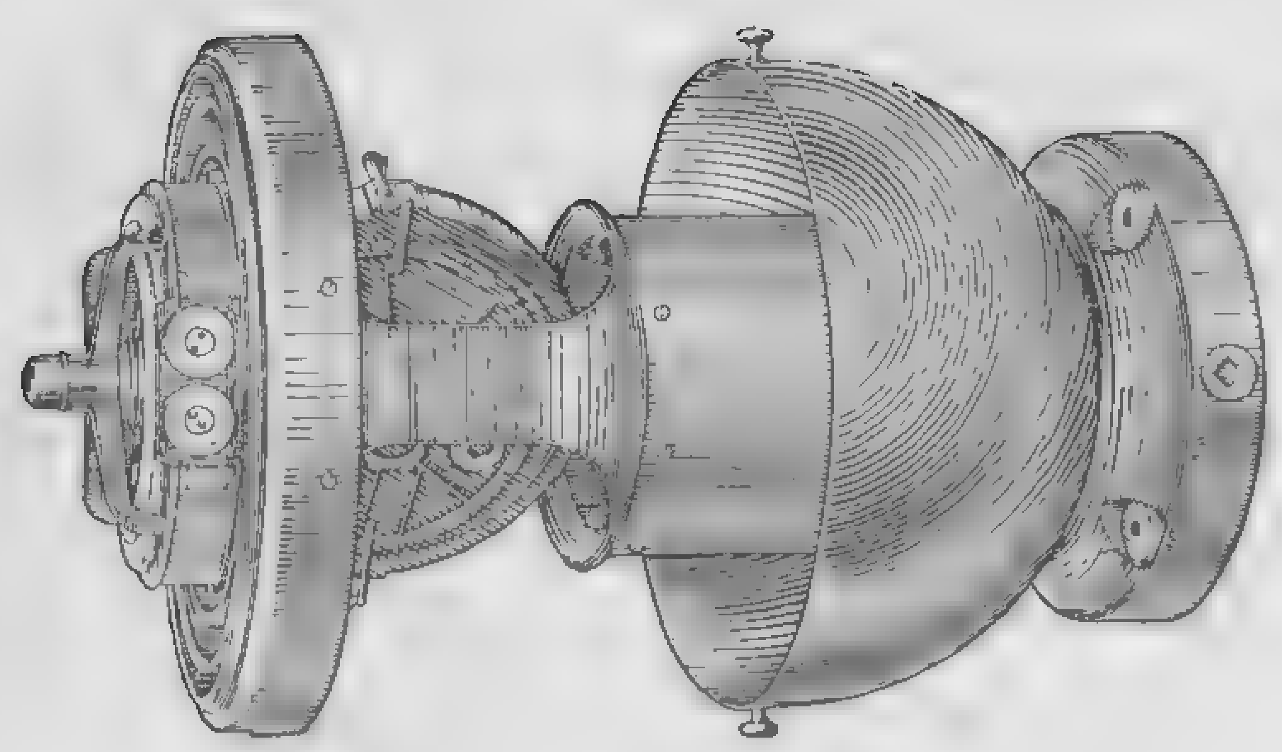
WILLIAM GILBERT
(1540–1603)

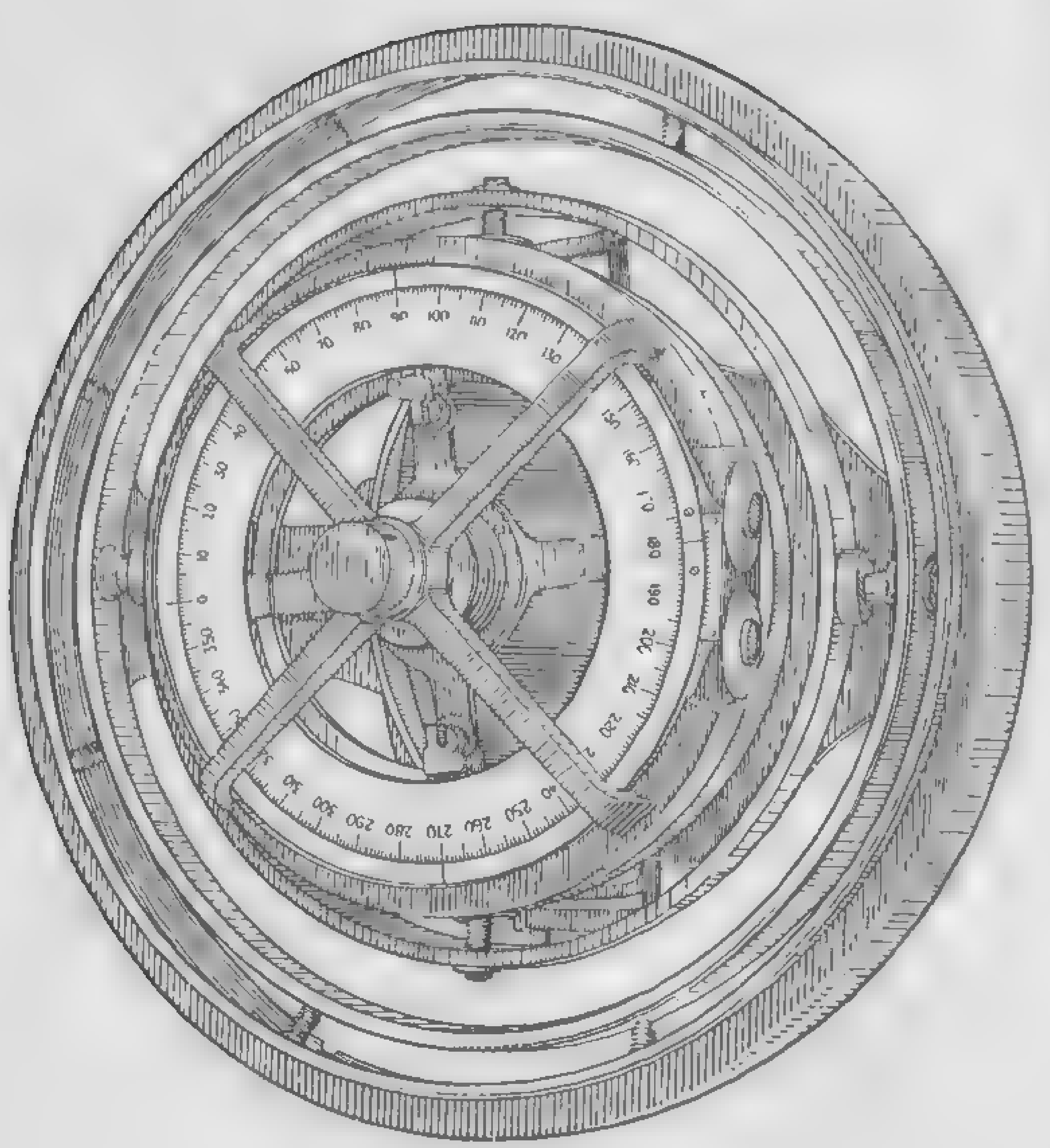
English physician and physicist; first Englishman to appreciate fully the value of experimental observations; first to discover through careful experimentation that the compass points to the north not because of some influence of the stars but because the earth is itself a great magnet; first to use the word "electricity"; first to discover that electrification can be produced by rubbing a great many different substances; author of the epoch-making book "De Magnete, etc.," published in London in 1600



THE EARTH'S MAGNETIC EQUATOR AND ISOGONIC LINES

The arrows show the direction of the compass needle





THE SPERRY GYROCOMPASS

Although the action of the mariner's compass was first correctly explained by Gilbert, the magnetic compass itself was invented by the Chinese and came to Europe about A.D. 1200. Until very recently it has been the sole reliance of the mariner. Today, however, it has found a competitor in the gyrocompass, which is now used to a considerable extent on battleships, and exclusively on submarines, within whose encircling shell of iron the magnetic compass will not function at all. It consists of a heavy wheel driven 8600 revolutions per minute about a horizontal axis by an induction motor. Because of its inertia this wheel tends to maintain the plane of its rotation. The revolution of the earth, however, tends to make it leave this plane unless the axis of rotation of the gyro and the earth's axis are already in the same plane. This calls into play a couple which swings the axis of the gyro into the same plane with the axis of the earth

graphic pole was found in 1831 by Sir James Ross in Boothia, Canada, latitude 70° 30′ N., longitude 95° W. It was located again in 1905 by Captain Amundsen (the discoverer of the geographic south pole in 1912) at a point a little farther west. Its approximate location is 70° 5′ N. and 96° 46′ W. It is probable that it shifts its position slowly.

275. Declination. The earliest users of the compass were aware that it did not point exactly north; but it was Columbus who, on his first voyage to America, made the discovery, much to the alarm of his sailors, that the direction of the compass needle changes as one moves about over the earth's surface. The chief reason for this variation is found in the fact that the magnetic poles do not coincide with the geographic poles; but there are also other causes, such as the existence of large deposits of iron ore, which produce local effects upon the needle. The number of degrees which the north pole of a compass needle at any given place on the earth points away from the true north is called its *declination* at that place. Each of the lines in the map opposite page 238 is so drawn that at each point on it the declination is the same. Lines drawn over the earth through points of equal declination are called *isogonic lines.* The heavy lines pass through all the points where the needle points exactly to the north. These lines correspond, therefore, to places where the declination is zero. Lines of zero declination are called *agonic lines.*

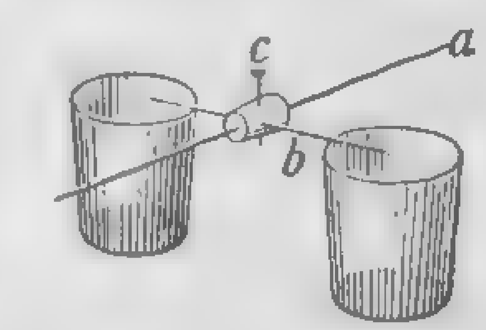


FIG. 218. Arrangement for showing dip

276. The dipping needle. Let an unmagnetized knitting needle *a* (Fig. 218) be thrust through a cork, and let a second needle *b* be inserted as shown. Let a pin *c* be adjusted until the system is in neutral equilibrium about *b* as an axis, when *a* is pointing east and west. Then let *a* be carefully magnetized by stroking one end of it, from the middle out, with the *N* pole of a strong magnet, and the other end, from the middle out, with the *S* pole of the same magnet. If the needle is allowed to swing in a north-and-south vertical plane it will dip at an angle of from 60° to 70° with the horizontal, *N* pole downward.

The experiment shows that in this latitude the earth's magnetic lines make a large angle with the horizontal. This angle between the earth's surface and the direction of the magnetic lines is called the *dip*, or *inclination*, of the needle. At Washington it is 71° 5′, and at Chicago 72° 50′. At the magnetic pole it is of course 90°, and at the so-called *magnetic equator*, which is an irregular curved line near the geographic equator, the dip is 0° (see map opposite page 238). The dipping needle is shown in Fig. 219.

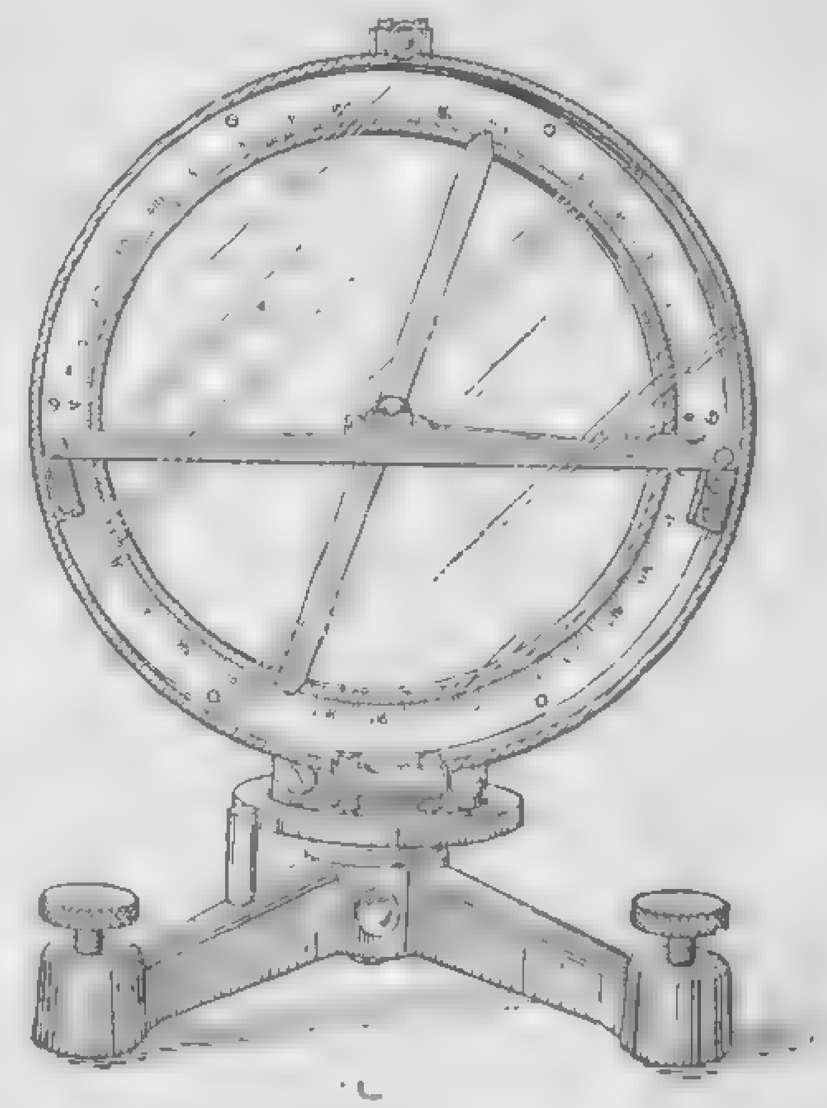


FIG. 219. The dipping needle

277. The earth's inductive action. That the earth acts like a great magnet may be very strikingly shown in the following way:

Hold a steel rod (for example, a tripod rod) parallel to the earth's magnetic lines (the north end slanting down at an angle of about 70° or 75°) and strike it a few sharp blows with a hammer. The rod will be found to have become a magnet with its upper end an *S* pole, like the north pole of the earth, and its lower end an *N* pole. If the rod is reversed and tapped again with the hammer, its magnetism will be reversed. If it is held in an east-and-west position and tapped, it will become demagnetized, as will be shown by the fact that either end of it will attract either end of a compass needle. In some respects a soft-iron rod is more satisfactory for this experiment than a steel rod, on account of the smaller retentivity.

SUMMARY. **Like poles repel; unlike poles attract.**

A unit pole is one which at a distance of 1 centimeter from an equal and similar pole repels it with a force of 1 dyne.

A magnetic line of force is the path along which an independent *N* pole tends to move.

A magnetic field of unit strength is one in which a unit pole experiences 1 dyne of force.

The declination at a given locality is the number of degrees by which the *N* pole points away from the true north.

The dip, or inclination, in a given locality is the angle between a horizontal plane and the direction of the dipping needle.

The magnetic equator is an irregular line drawn over the earth through points where the inclination is zero.

QUESTIONS AND PROBLEMS *

1. Devise an experiment which will show that a piece of iron attracts a magnet just as truly as the magnet attracts the iron.

2. In testing a needle with a magnet to see if the needle is magnetized why must you get *repulsion* before you can be sure it is magnetized?

3. Given two bar magnets, the poles of which are not marked, how would you (1) locate the north-seeking pole of each? (2) determine which is the more strongly magnetized?

4. Make a diagram to show the general shape of the lines of force between unlike poles of two bar magnets; between like poles.

5. When a piece of soft iron is made a temporary magnet by bringing it near the *N* pole of a bar magnet, will the end of the iron nearest the magnet be an *N* pole or an *S* pole? Explain.

6. Explain, on the basis of induced magnetization, the process by which a magnet attracts a piece of soft iron.

FIG. 220

7. Two bar magnets of equal strength are combined as in Fig. 220 (1) and then as in Fig. 220 (2). Diagram their magnetic lines of force as you imagine them to be in the two cases. Test by using iron filings and cardboard; also by lifting a bunch of small nails.

8. Examine the map opposite page 238 and tell where a compass would point north; south; east; west.

9. Examine the map opposite page 238 to locate the line of no dip (the magnetic equator). Does it ever coincide with the geographical equator? If so, where?

* Supplementary questions and problems for Chapter XII are given in the Appendix.

CHAPTER XIII

STATIC ELECTRICITY

General Facts of Electrification

278. Electrification by friction. If a piece of hard rubber or a stick of sealing wax is rubbed with flannel or cat's fur and then brought near some dry pith balls, bits of paper, or other light bodies, these bodies are found to jump toward the rod. This sort of attraction, so familiar to us from the behavior of our hair in winter when we comb it with a rubber comb, was observed as early as 600 B.C., when Thales of Greece commented on the fact that rubbed amber draws to itself threads and other light objects. But it was not until A.D. 1600 that Dr. William Gilbert, physician to Queen Elizabeth, and sometimes called the father of the modern science of electricity and magnetism, discovered that the effect could be produced by rubbing together a great variety of other substances besides amber and silk, such, for example, as glass and silk, sealing wax and flannel, hard rubber and cat's fur, etc.

The effect produced upon these various substances by friction was named by Gilbert (see opposite page 238) *electrification*, after the Greek name *electron*, meaning "amber." *Thus a body which, like rubbed amber, has been endowed with the property of attracting light bodies is said to have been electrified, or to have been given a charge of electricity.* In this statement nothing is said about the nature of electricity. We simply define an electrically charged body as one that has been put into the condition in which it acts toward light bodies like the rubbed amber or the rubbed sealing wax. We do not know with certainty what the ultimate nature of

electricity is, but we are fairly sure of the laws that govern its action. The following sections deal with these laws.

279. Positive and negative electricity. Let a pith ball suspended by a silk thread, as in Fig. 221, be touched to a glass rod that has been rubbed with silk; the ball will thus be put into the condition in which it is strongly repelled by this rod. Next let a stick of sealing wax or an ebonite rod that has been rubbed with cat's fur or flannel be brought near the charged ball. It will be found that it is not repelled but, on the contrary, is very strongly attracted. Similarly, if the pith ball has touched the sealing wax so that it is repelled by it, it is found to be strongly attracted by the glass rod. Again, two pith balls both of which have been in contact with the glass rod are found to repel each other, but pith balls one of which has been in contact with the glass rod and the other with the sealing wax attract each other.

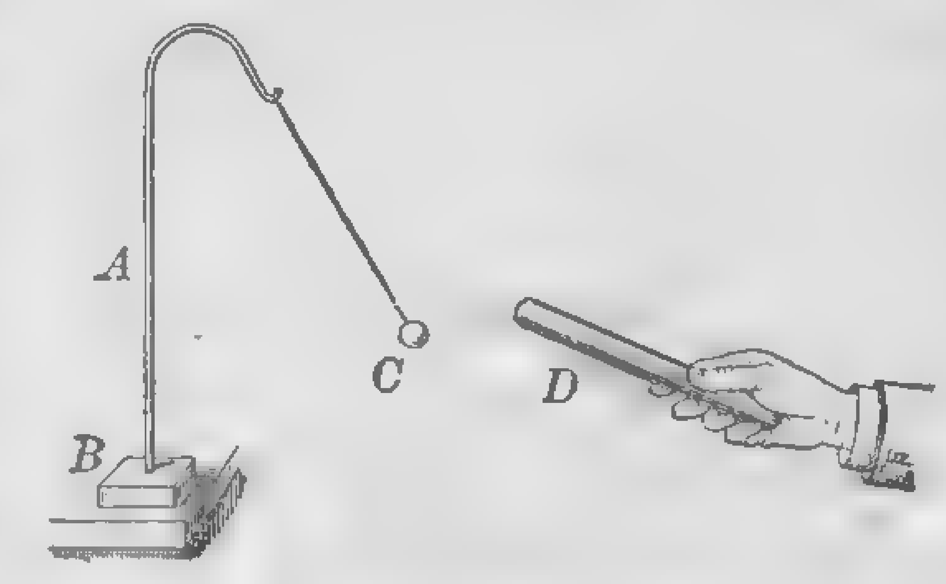


Fig. 221. Pith-ball electroscope

Evidently, then, the electrifications imparted to glass by rubbing it with silk and to sealing wax by rubbing it with flannel are opposite in the sense that an electrified body which is attracted by one is repelled by the other. We say, therefore, that there are two kinds of electrification. Benjamin Franklin arbitrarily introduced the terms *positive* and *negative*, or + and −, to designate these two kinds of electrification. Thus, a *positively electrified body* is one which acts with respect to other electrified bodies like a *glass rod that has been rubbed with silk*, and a *negatively electrified body* is one which acts like a piece of *sealing wax that has been rubbed with flannel*. These facts and definitions may be stated in the following general law: *Electrical charges of like kind repel each other, and charges of unlike kind attract each other.* The forces of attraction or repulsion are found, like those of gravitation and magnetism, *to decrease as the square of the distance increases.*

280. Measurement of electrical quantities. The fact of attraction and repulsion is taken as the basis for the definition and measurement of so-called *quantities* of electricity. Thus, a small charged body is said to contain 1 unit of electricity when it will repel with a force of 1 dyne an exactly equal and similar charge placed 1 cm. away. The number of units of electricity on any charged body is then measured by the force that it exerts upon a unit charge placed at a given distance from it; for example, a charge that at a distance of 10 cm. repels a unit charge with a force of 1 dyne contains 100 units of electricity, for this means that at a distance of 1 cm. it would repel the unit charge with a force of 100 dynes (see § 279).

281. Conductors and nonconductors. Let an electroscope E (Fig. 222), consisting of a pair of gold leaves a and b, suspended from an insulated metal rod r and protected from air currents by a case J, be connected with the metal ball B by means of a wire. Now let an ebonite rod be electrified and rubbed over B. The gold leaves will immediately diverge, showing that a portion of the electrical charge placed upon B has been carried by the wire to the gold leaves, where it makes them diverge in accordance with the law that bodies charged with the same kind of electricity repel each other.

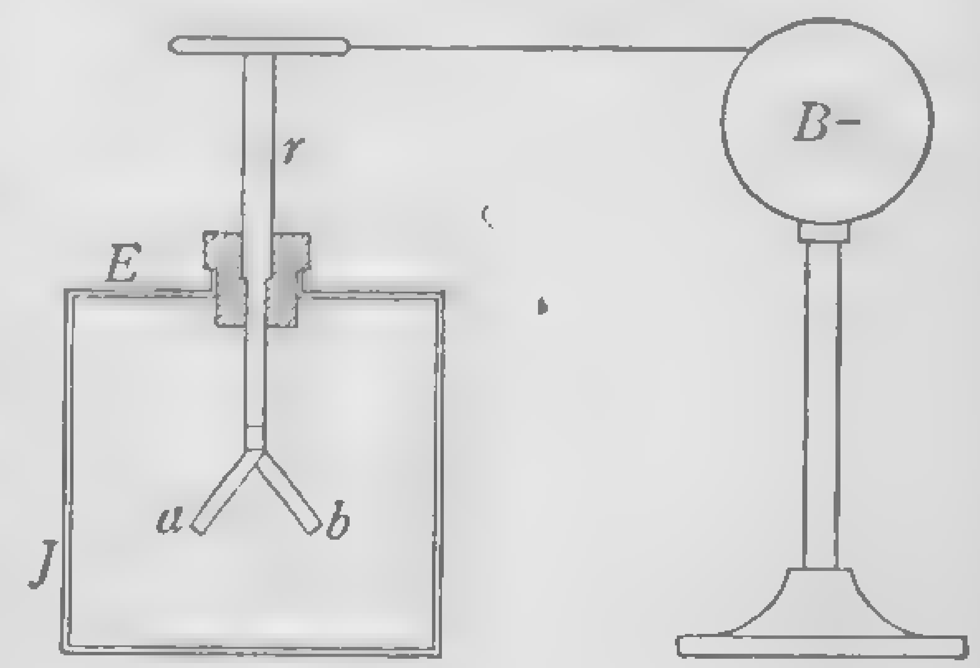


FIG. 222. Illustrating conduction

Let the experiment be repeated when E and B are connected with a thread of silk or a long rod of wood instead of the metal wire. No divergence of the leaves will be observed. If a moistened thread connects E and B, the leaves will be seen to diverge slowly when the ball B is charged, showing that a charge is carried slowly by the moist thread.

These experiments make it clear that while electrical charges pass with perfect readiness from one point to another in a wire, they are quite unable to pass along dry silk or wood, and pass with difficulty along moist silk. We are therefore accustomed to divide substances into two classes, *conductors* and *nonconductors* (or *insulators*), according to their ability to transmit electrical charges from point to point. Thus, metals and solutions of salts and acids in water are all conductors of electricity, and glass, porcelain, rubber, mica, shellac, wood, silk, vaseline, turpentine, paraffin, and oils are insulators. No hard-and-fast line, however, can be drawn between conductors and nonconductors, since all so-called insulators conduct to some slight extent, and the so-called conductors differ greatly in the facility with which they transmit charges.

The fact of conduction brings out sharply one of the most essential distinctions between electricity and magnetism. Magnetic poles exist only in iron and steel; electrical charges may be communicated to any body whatever, provided it is insulated. These charges pass over conductors and can be transferred by contact from one body to any other, whereas magnetic poles remain fixed in position and are wholly uninfluenced by contact with other bodies unless these bodies are themselves magnets.

282. Electrostatic induction. Let the ebonite rod be electrified by friction and slowly brought toward the knob of the gold-leaf electroscope (Fig. 223). The leaves will be seen to diverge, even though the rod does not approach to within a foot of the electroscope.

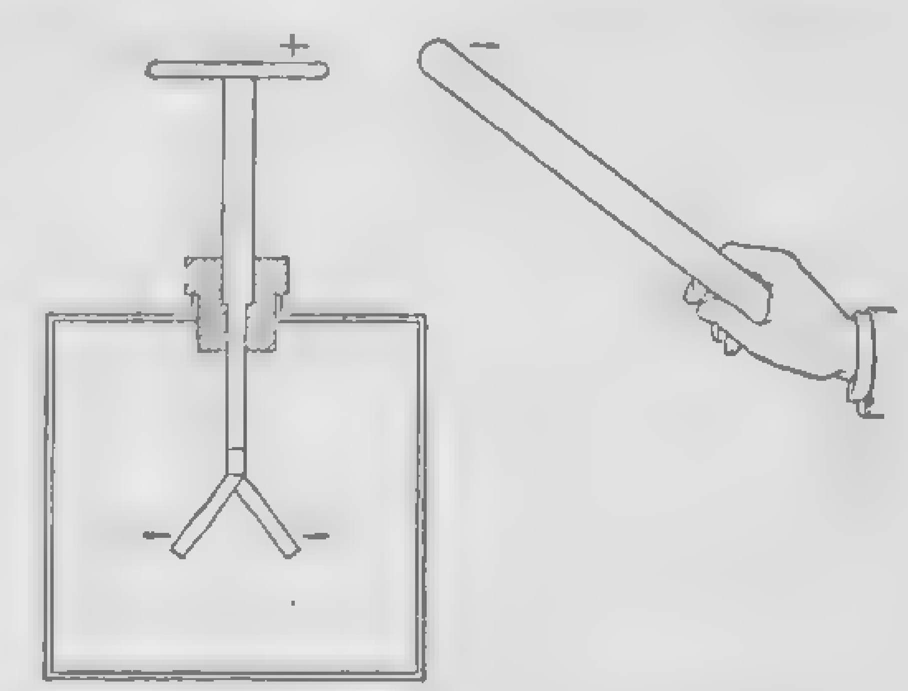


FIG. 223. Illustrating induction

This makes it clear that the mere *influence* which an electrical charge exerts upon a conductor placed in its neighborhood is able to produce electrification in that conductor. This method of producing electrification is called *electrostatic induction.*

As soon as the charged rod is removed, the leaves will be seen to collapse completely. This shows that this form

of electrification is only a temporary phenomenon which is due simply to the presence of the charged body in the neighborhood.

283. Nature of electrification produced by induction. Let a metal ball *A* (Fig. 224) be strongly charged by rubbing it with a charged rod, and let it then be brought near an insulated * metal body *B* provided with pith balls or strips of paper *a*, *b*, *c*, as shown. The divergence of *a* and *c* will show that the ends of *B* have received electrical charges because of the presence of *A*, and the failure of *b* to diverge will show that the middle of *B* is uncharged. Furthermore, the rod that charged *A* will be found to repel *c* but to attract *a*.

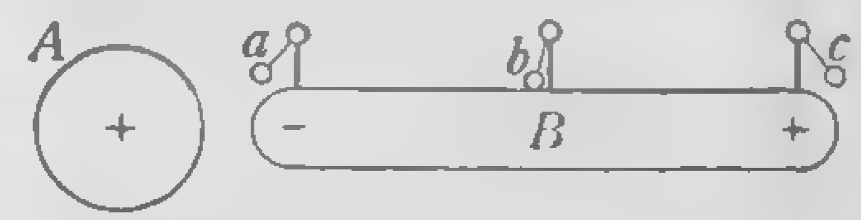


FIG. 224. Nature of induced charges

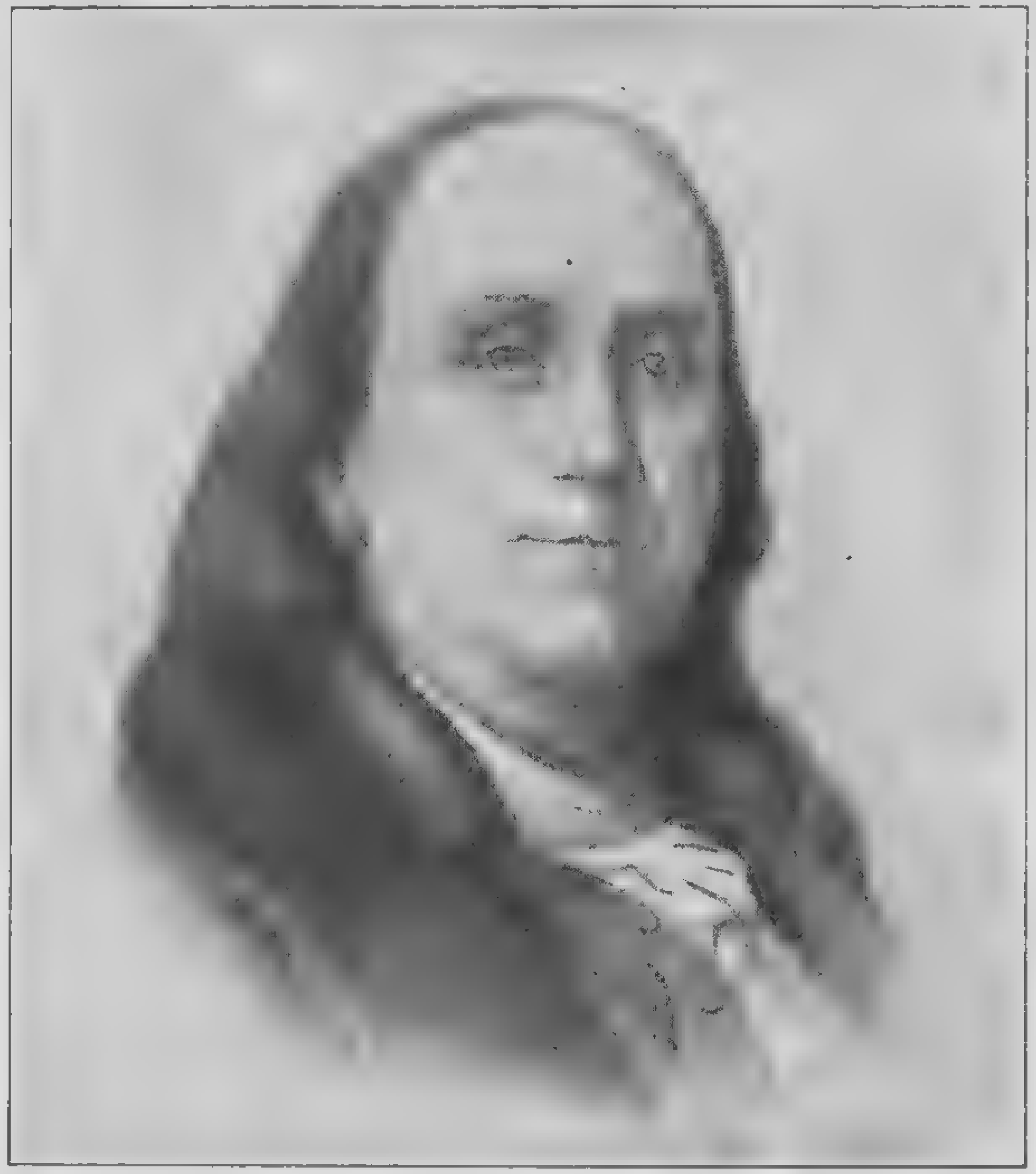
We conclude, therefore, that *when a conductor is brought near a charged body, the end away from the inducing charge is electrified with the same kind of electricity as that on the inducing body, while the end toward the inducing body receives electricity of the opposite kind.*

284. The electron theory of electricity. The atoms of all substances are now known to contain as constituents both positive and negative electricity, the latter existing in the form of minute corpuscles, or electrons, each of which has a mass $\frac{1}{1845}$ of that of the hydrogen atom. These electrons are grouped in some way about the positive electricity as a nucleus. The sum of the negative charges of these electrons is equal to the positive charge of the nucleus, so that in its normal condition the whole atom is neutral, or uncharged. But in conductors electrons are continually getting loose from the atoms and reëntering other atoms, so that at any given instant there are in every conductor a number of free negative electrons and a corresponding number of atoms which have lost electrons and which are therefore positively charged.

* Sulphur is practically a perfect insulator in all weathers, wet or dry. Metal conductors of almost any shape resting upon pieces of sulphur will serve the purposes of this experiment in summer or winter.

FRANKLIN'S KITE EXPERIMENT

In June, 1752, Franklin demonstrated the identity of the electric spark and lightning. To prevent his kite from being torn in the rain he made it of a silk handkerchief. The lower end of the kite string and a silk ribbon were tied to the ring of a key, and, to prevent any charge that might appear upon the string and the key from escaping through his body to the earth, he held the kite by grasping the insulating silk ribbon. Standing under a shed to keep the ribbon dry, Franklin, by presenting his knuckle to the key, obtained sparks similar to those produced by his electric machine. With these sparks he charged his Leyden jar and used it to give a shock. Indeed, he performed with lightning all the experiments which he had previously performed with sparks from his frictional machine. The experiment is *dangerous* and should not be attempted by inexperienced persons



BENJAMIN FRANKLIN (1706–1790)

Celebrated American statesman, philosopher, and scientist; born at Boston, the sixteenth child of poor parents; printer and publisher by occupation; pursued scientific studies in electricity as a diversion rather than as a profession; first proved that the two coats of a Leyden jar are oppositely charged; introduced the terms "positive" and "negative" electricity; proved the identity of lightning and frictional electricity by flying a kite in a thunderstorm and drawing sparks from the insulated lower end of the kite string; invented the lightning rod; originated the one-fluid theory of electricity, which regarded a positive charge as indicating an excess and a negative charge a deficiency in a certain normal amount of an all-pervading electrical fluid

Such a conductor would, as a whole, show no charge of either positive or negative electricity. But as soon as a body charged, for example, positively (Fig. 224) is brought near such a conductor, the free negative electrons are attracted to the near end, leaving behind them the positively charged but immovable atoms. On the other hand, if a negatively charged body is brought near the conductor, the negative electrons stream away and the near end is left with the immovable plus atoms. As soon as the inducing charge is removed, the conductor becomes neutral again, because the little negative corpuscles return to their former positions under the influence of the attraction of the positive atoms. This is the present-day picture of the mechanism of electrification by induction.

The charge of one electron is called the elementary electrical charge. Its value has recently been accurately measured. There are 2,095,000,000 of them in one of the units defined in § 280. *Every electrical charge consists of an exact number of these ultimate electrical atoms.* (See opposite p. 479.)

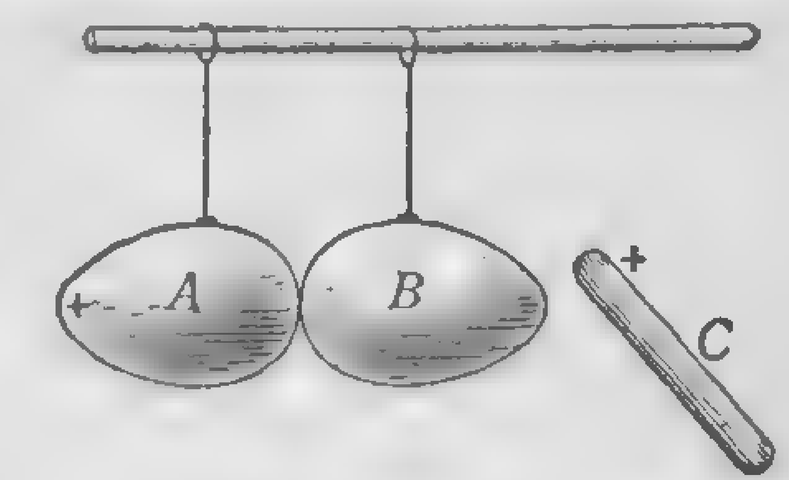


FIG. 225. Obtaining a plus and a minus charge by induction

285. Charging by induction. Let two metal balls or two eggshells, A and B, which have been gilded or covered with tin foil, be suspended by silk threads and touched together, as in Fig. 225. Let a positively charged body C be brought near them. As described above, A and B will at once exhibit evidences of electrification; that is, A will repel a positively charged pith ball, and B will attract it. If C is removed while A and B are still in contact, the separated charges reunite and A and B cease to exhibit electrification; but if A and B are separated from each other while C is in place, A will be found to remain positively charged and B negatively charged. This may be proved either by the attractions and repulsions which they show for charged rods brought near them or by the effects produced upon a charged electroscope brought into their vicinity, the leaves falling together when it is brought near one and spreading apart when brought near the other.

We see, therefore, that *if we cut in two, or separate into two parts, a conductor while it is under the influence of an electrical charge, we obtain two permanently charged bodies, the remoter part having a charge of the same sign as that of the inducing charge, and the near part having a charge of unlike sign.* Under the influence of the positive charge on C the negative electrons moved out of A into B, which act made A positive and B negative.

Let the insulated conductor B (Fig. 226) be touched at a by the finger while a positively charged rod C is near it. Then let the finger be removed, and after it the rod C. If now a negatively charged pith ball is brought near B, it will be repelled, showing that B has become negatively charged. In this experiment the body of the experimenter corresponds to the egg A of the preceding experiment, and removing the finger from B corresponds to separating the two eggshells. Let the last experiment be repeated with only this modification: that B is touched at b rather than at a. When B is again tested with the pith ball, it will still be found to have a negative charge, exactly as when the finger was touched at a.

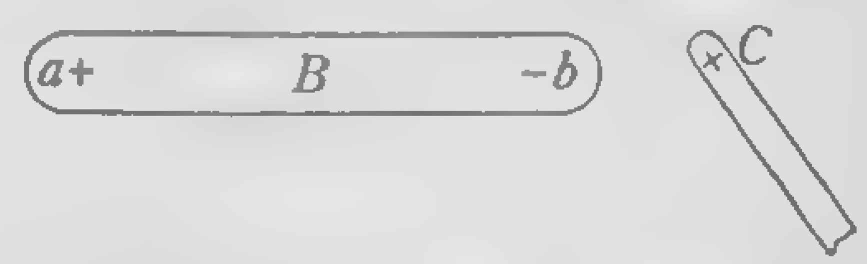


FIG. 226. A body charged by induction has a charge of sign opposite to that of the inducing charge

We conclude, therefore, that no matter where the insulated body B is touched, *the sign of the charge left upon it is always opposite to that of the inducing charge.* This is because the negative electricity, that is, the electrons, can under no circumstances escape from b so long as C is present, for they are *bound* by the attraction of the positive charge on C. Indeed, the final negative charge on B is due merely to the fact that the positive charge on C pulls electrons into B from the finger, no matter where B is touched. In the same way, if C had been negative, it would have pushed electrons off from B through the finger and thus have left B positively charged.

286. Charging the electroscope by induction. Let a glass rod which has been rubbed with silk be brought near the knob of the electroscope. The leaves at once diverge (Fig. 227 (1)). Let the knob be touched with the finger while the rod is held in place. The leaves will fall together (Fig. 227 (2)). Let the finger be removed (Fig. 227 (3)), and then the rod. The leaves will fly apart again (Fig. 227 (4)).

The electroscope is now charged by induction; and as the charge on the glass rod is +, the charge on the electroscope must be —. If this conclusion is tested by bringing the charged glass rod near the electroscope, the leaves will fall together as the rod approaches the knob. This proves that the charge on the electroscope is —. If the empty neutral hand approaches the knob, the leaves will fall. Explain.

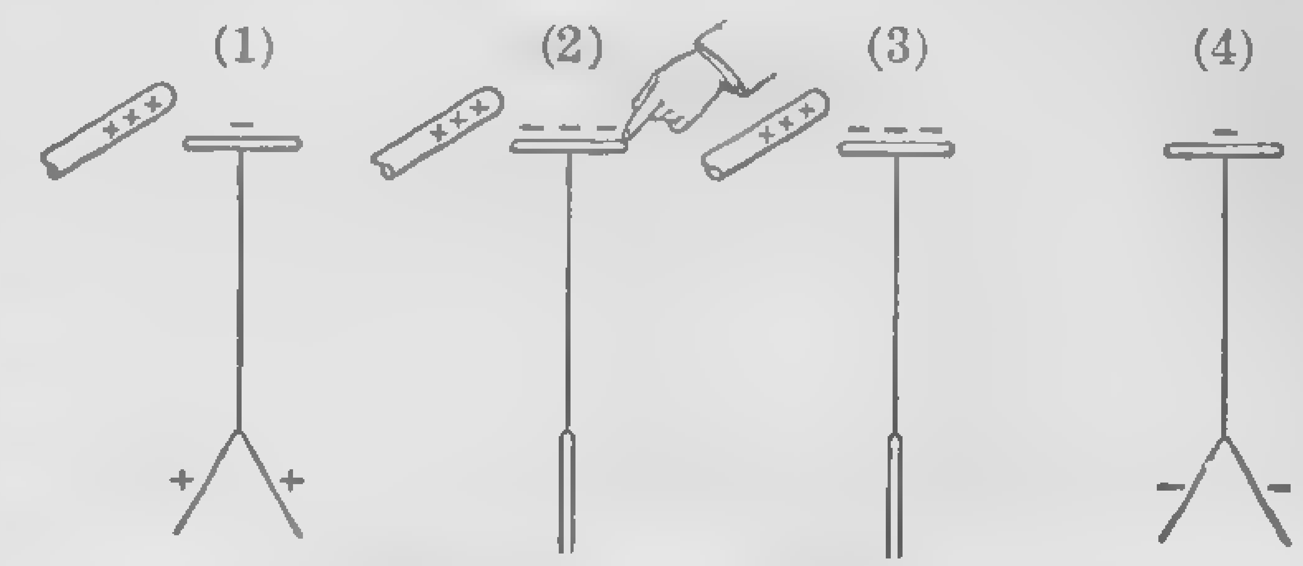


FIG. 227. Charging the electroscope by induction

287. Plus and minus electricities always appear simultaneously and in equal amounts. Let an ebonite rod be completely discharged by passing it quickly through a Bunsen flame. Let a flannel cap having a silk thread attached be slipped over the rod, as in Fig. 228, and twisted rapidly round a number of times. When rod and cap together are held near a charged electroscope, no effect will be observed; but if the cap is pulled off, it will be found to be positively charged, and the rod will be found to have a negative charge.

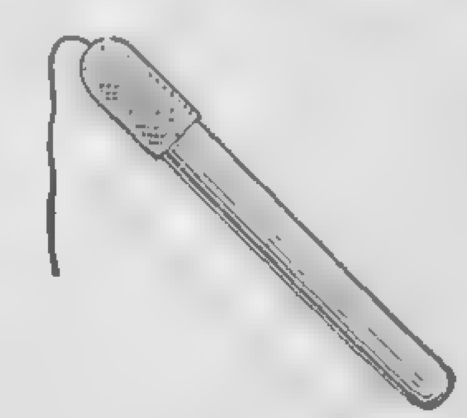


FIG. 228. Plus and minus electricities always developed in equal amounts

Since the two together produce no effect, the experiment shows that the plus and minus charges were equal in amount. This experiment confirms the view already brought forward in connection with induction, that *electrification always consists in a separation of plus and minus charges that already exist in equal amounts within the bodies in which the electrification is developed.*

Summary. Like electrical charges repel; unlike charges attract.

A unit charge of electricity is that charge which at a distance of 1 centimeter from an exactly equal and similar charge repels it with a force of 1 dyne.

A neutral body contains equal amounts of + and − electricity.

To charge a body positively (+) some of the negative electrons of the body must be removed from it; the more, the greater the + charge.

To charge a body negatively (−) negative electrons from some other body must be added to it; the more, the greater the − charge.

When a body is charged by induction it always receives a charge opposite to that on the charging body.

Whenever a charge of electricity is developed on one body, an equal but opposite quantity is developed on some other body.

QUESTIONS AND PROBLEMS

1. A pith ball is covered with gold leaf and suspended by a silk thread. While a + glass rod is held near it, the pith ball exhibits a tendency to move toward the rod. Make a diagram to show the electrical condition of the bodies concerned.

2. Why is the pith ball attracted rather than repelled?

3. In the case of the rod attracting the pith ball after electrostatic induction, do you see anything analogous to a magnet attracting a nail after magnetic induction? Explain the attraction, using diagrams for both cases.

4. By aid of a series of diagrams explain all the steps in charging an electroscope by induction with a − ebonite rod.

5. As a + rod approached a negatively charged electroscope the leaves came together; but as the + rod came still closer, the leaves diverged again. Explain.

6. Given a gold-leaf electroscope, a glass rod, and a piece of silk, how, in general, would you proceed to test the sign of the electrification of an unknown charge?

7. Charge a gold-leaf electroscope by induction from a glass rod. Warm a piece of paper and stroke it on the clothing. Hold it over the charged electroscope. If the divergence of the gold leaves is increased, is the charge on the paper + or −? If the divergence is decreased, what is the sign of the charge on the paper?

8. If pith balls or any light figures are placed between two plates (Fig. 229), one of which is connected to earth and the other to one knob of an electrical machine in operation, the figures will bound back and forth between the two plates as long as the machine is operated. Explain.

9. If you hold a brass rod in the hand and rub it with silk, the rod will show no sign of electrification; but if you hold the brass rod with a piece of sheet rubber and then rub it with silk, you will find it electrified. Explain.

10. State as many differences as you can between the phenomena of magnetism and those of electricity.

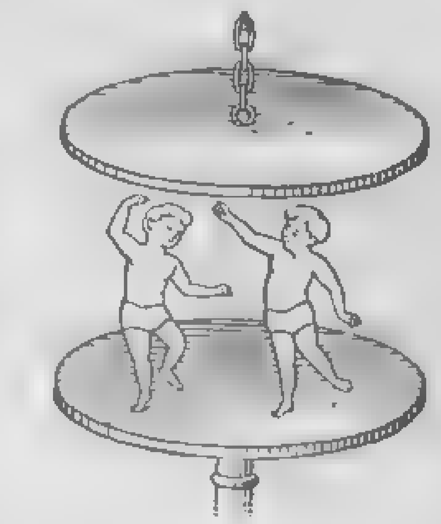


Fig. 229

Distribution of Electrical Charge upon Conductors

288. Electrical charges reside only upon the outside surface of conductors. Let a deep tin cup (Fig. 230) be placed upon an insulating stand and charged as strongly as possible either from an ebonite rod or from an electrical machine. If now a smooth metal ball suspended by a silk thread is touched to the *outside* of the charged cup and then brought near the knob of a charged electroscope, it will show a strong charge; but if it is touched to the *inside* of the cup, it will show no charge at all.

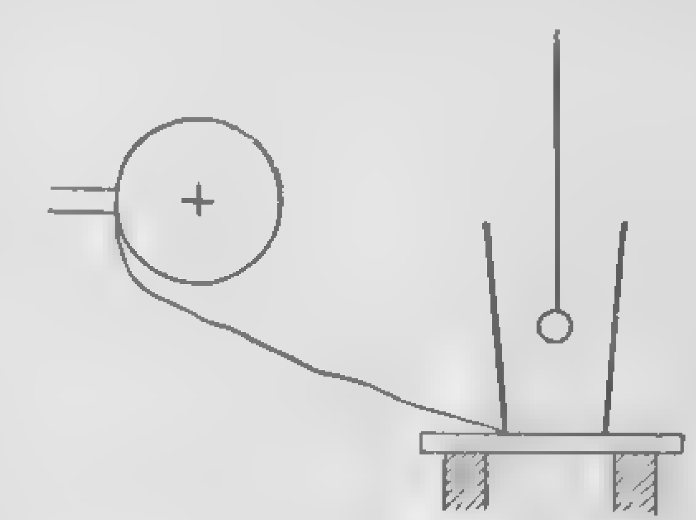


Fig. 230. Proof that charge resides on surface

These experiments show that *an electrical charge resides entirely on the outside surface of a conductor.* This result might have been inferred from the fact that all the little electrical charges of which the total charge is made up repel each other and therefore move through the conductor until they are, on the average, as far apart as possible.

289. Density of charge greatest where curvature of surface is greatest. Since all the parts of an electrical charge tend, because of their mutual repulsions, to get as far apart as possible, we infer that if a charge of either sign is placed

upon an oblong conductor like that of Fig. 231 (1) it will distribute itself so that the electrification at the ends will be stronger than that at the middle.

To test this inference let a proof plane — a flat metal disk (for example, a cent) provided with an insulating handle — be touched to one end of such a charged body, the charge conveyed to a gold-leaf electroscope, and the amount of separation of the leaves noted. Then let the experiment be repeated when the proof plane touches the middle of the body. The separation of the leaves in the latter case will be found to be very much less than in the former. If we should test the distribution on a pear-shaped body (Fig. 231 (2)) in the same way, we should find the density of electrification considerably greater on the small end than on the large one. By density of electrification is meant the quantity of electricity on unit area of the surface.

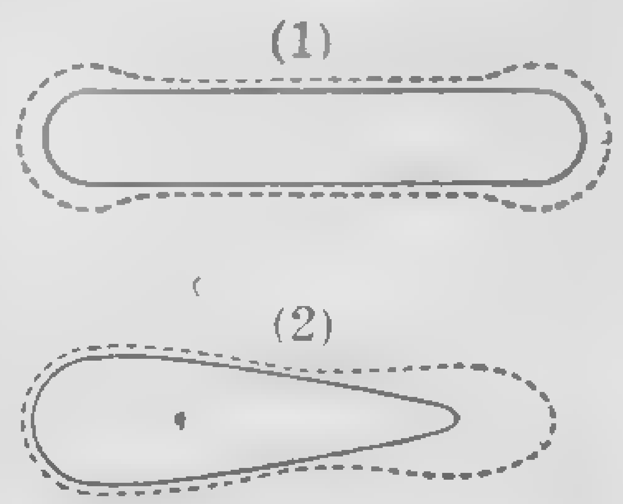


FIG. 231. Distribution of charge over oblong bodies

290. Discharging effect of points. The foregoing experiments indicate that if one end of a pear-shaped body is made more and more pointed, then, when the body is charged, the electrical density on this end will become greater and greater. The following experiment will show what happens when the conductor is provided with a sharp point.

Let a very sharp needle be attached to any smooth insulated metal body provided with paper or pith-ball indicators, as in Fig. 224, p. 246. If the body is now charged either with a rubbed rod or with an electrical machine, as soon as the supply of electricity is stopped the paper indicators will immediately fall, showing that the body is losing its charge. To show that this is certainly due to the effect of the point, remove the needle and repeat. The indicators will fall very slowly if at all.

The experiment shows that the electrical density on the point is so great that the charge escapes from it into the air. This is because the intense charge on the point causes many of the adjacent molecules of the air to lose an electron. This leaves these molecules positively charged. The free electrons

attach themselves to neutral molecules, thus charging them negatively. One set of these electrically charged molecules (called *ions*) is attracted to the point and the other is repelled from it. The former set move to the conductor, give up their charges to it, and thus neutralize the charge on it.

The effect of points may be shown equally well by charging the gold-leaf electroscope and holding a needle in the hand within a few inches of the knob. The leaves will fall together rapidly. In this case the needle point becomes electrified by induction and discharges to the knob electricity of the opposite kind to that on the knob, thus neutralizing its charge. An entertaining variation of the last experiment is to attach a tassel of tissue paper to an

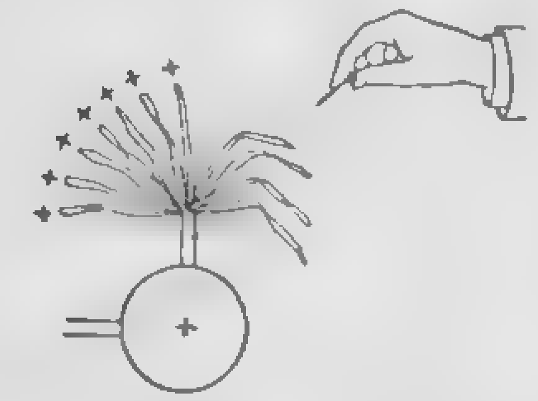


FIG. 232. Discharging effect of points

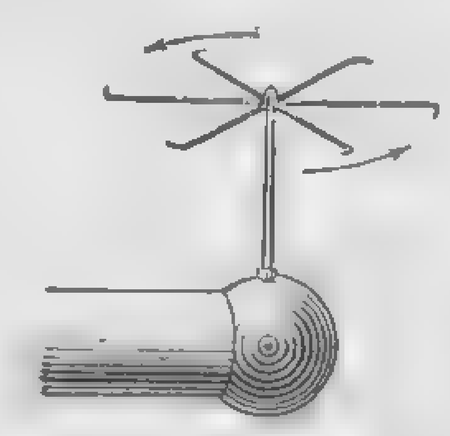


FIG. 233. The electric whirl

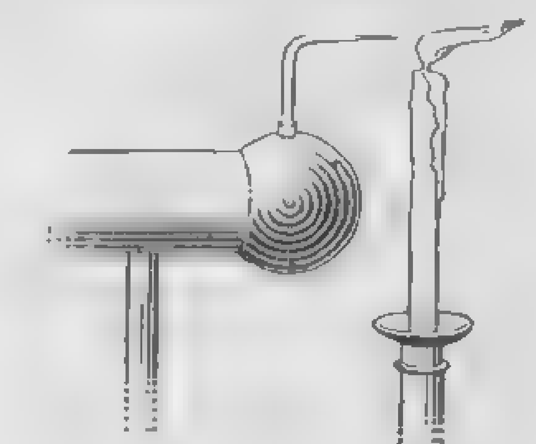


FIG. 234. The electric wind

insulated conductor and electrify it strongly. The paper streamers will under their mutual repulsions stand out in all directions, but as soon as a needle point is held in the hand near them, they will fall together (Fig. 232), being discharged as described above.

291. The electric whirl. Let an electric whirl (Fig. 233) be balanced upon a pin point and attached to one knob of an electrical machine. As soon as the machine is started, the whirl will rotate rapidly in the direction of the arrows.

The explanation is as follows: The air close to each point is *ionized*, as explained in § 290. The ions of sign unlike that of the charge on the point are drawn to the point and discharged. The other set of ions is repelled. But since this repulsion is mutual, the point is pushed back with the same force with which these ions are pushed forward; hence the rotation. The repelled ions in their turn drag the air with them in their forward motions and thus produce the *electric wind*, which may be detected easily by the hand or by a candle flame (Fig. 234).

292. Lightning and lightning rods. It was in 1752, during a thunderstorm, that Franklin (see opposite page 247) sent up his historic kite (see opposite page 246). This kite was provided with a pointed wire at the top. As soon as the hempen kite-string had become wet Franklin succeeded in drawing ordinary electric sparks from a key attached to the lower end. This experiment demonstrated for the first time that thunderclouds carry ordinary electrical charges which may be drawn from them by points, just as the charge was drawn from the tassel in the experiment of § 290. It also showed that lightning is nothing but a huge electric spark (see opposite pages 258 and 259). Franklin applied this discovery in the invention of the lightning rod. The way in which the rod discharges the cloud and protects the building is as follows: As the charged cloud approaches the building, it induces an opposite charge in the rod. This induced charge escapes rapidly and quietly from the sharp point in the manner explained above, thus neutralizing the charge of the cloud.

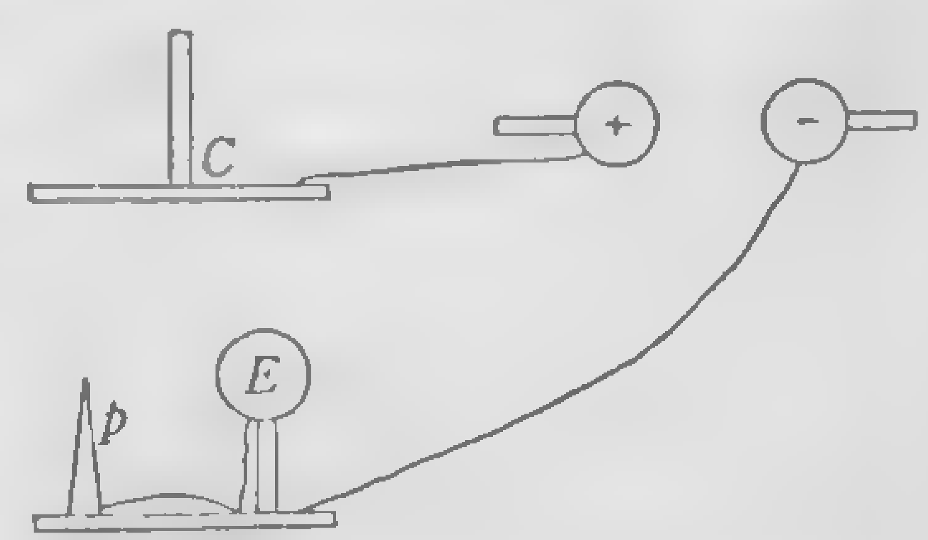


FIG. 235. Illustrating the action of a lightning rod

To illustrate, let a metal plate C (Fig. 235) be supported above a metal ball E, and let C and E be attached to the two knobs of an electrical machine. When the machine is started, sparks will pass from C to E. But if a point p is connected to E, the sparking will cease; that is, the point will protect E from the discharges, even though the distance Cp be considerably greater than CE.

The lower end of a lightning rod should be buried deep enough to be always surrounded by moist earth, since dry earth is a poor conductor. It will be seen, therefore, that lightning rods protect buildings not because they conduct the lightning to earth, but because they prevent the formation of powerful charges in the neighborhood of the buildings on which they are placed.

Flashes of lightning over a mile long have often been observed (see opposite page 258). Thunder is due to the violent expansion of heated air along the path of discharge. The roll of thunder is due to reflections of the sound from clouds, hills, etc.*

SUMMARY. An electrical charge resides on the outside of a conductor because of the mutual repulsion of the like parts of the charge.

The electrical density of a charge is greatest on sharp curves; on points, it is so great that the adjacent air becomes ionized.

The discharging effect of points is due to the conducting power of ionized air in the vicinity of the point.

Lightning rods owe their usefulness to the discharging effects of their points.

QUESTIONS AND PROBLEMS

1. Will a solid sphere hold a larger charge of electricity than a hollow one of the same diameter?

2. Represent by a drawing the electrical condition of a tower just before it is struck by lightning, assuming the cloud at this particular time to be powerfully charged with + electricity.

3. When a negatively electrified cloud passes over a house provided with a lightning rod, the charged points ionize the air, and the charged cloud is thereby rendered less dangerous. Explain.

POTENTIAL AND CAPACITY

293. Potential difference. There is a very instructive analogy between the use of the word "potential" in electricity and "pressure" in hydrostatics. For example, if water will flow from tank A to tank B through the connecting pipe R (Fig. 236), we infer that the hydrostatic pressure at a must be greater than that at b, and we attribute the flow directly to this difference in pressure. In exactly the same way, if, when two bodies A and B (Fig. 237) are connected by a conducting wire r, a charge of + electricity is found to pass

* A laboratory exercise on static electrical effects should follow the discussion of this section. See, for example, Experiment 33 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

from A to B (that is, if electrons are found to pass from B to A), we say that the electrical potential is higher at A than at B, and we assign this *difference of potential* as the cause of the flow.* Thus, just as water tends to flow from points of higher hydrostatic pressure to points of lower hydrostatic pressure, so electricity tends to flow from points of higher electrical pressure, or potential, to points of lower electrical pressure, or potential.

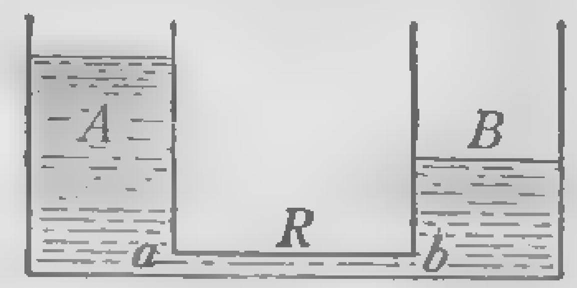


FIG. 236. Illustrating hydrostatic pressure

Again, if water is not continuously supplied to one of the tanks A or B of Fig. 236, we know that the pressures at a and b must soon become the same. Similarly, if no electricity is supplied to the bodies A and B of Fig. 237, their potentials very quickly become the same. In other words, *all points on a system of connected conductors in which the electricity is in a stationary, or static, condition are at the same potential.* This result follows at once from the fact of mobility of electrical charges through conductors.

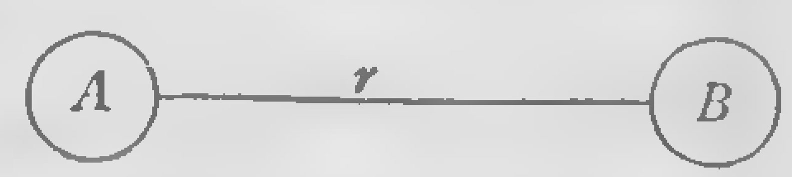


FIG. 237. Illustrating electrical pressure

But if water is continuously poured into A and removed from B (Fig. 236), the pressure at a will remain permanently above the pressure at b, and a continuous flow of water will take place through R. So, if A (Fig. 237) is connected with an electrical machine and B to earth, a permanent potential difference will exist between A and B, and a continuous current of electricity will flow through r. Difference in potential is commonly denoted simply by the letters P.D. (Potential Difference).

* Franklin thought that it was the positive electricity which moved through a conductor, and he conceived the negative as inseparably associated with the atoms. Hence it became a universally recognized convention to regard electricity as moving through a conductor in the direction in which a + charge would have to move in order to produce the observed effect. It is not desirable to attempt to change this convention now, even though the electron theory has exactly inverted the rôles of the + and − charges.

294. Some methods of measuring potentials. The simplest and most direct way of measuring the potential difference between two bodies is to connect one to the knob, the other to the conducting case,* of an electroscope. The amount of separation of the gold leaves is a measure of the P.D. between the bodies. The unit in which P.D. is usually expressed is called the *volt.* It will be accurately defined in § 335. It will be sufficient here to say that it is approximately equal to the electrical pressure between the ends of copper and zinc strips when dipped in dilute sulphuric acid or to two thirds of the electrical pressure between the zinc and carbon terminals of the familiar dry cell.

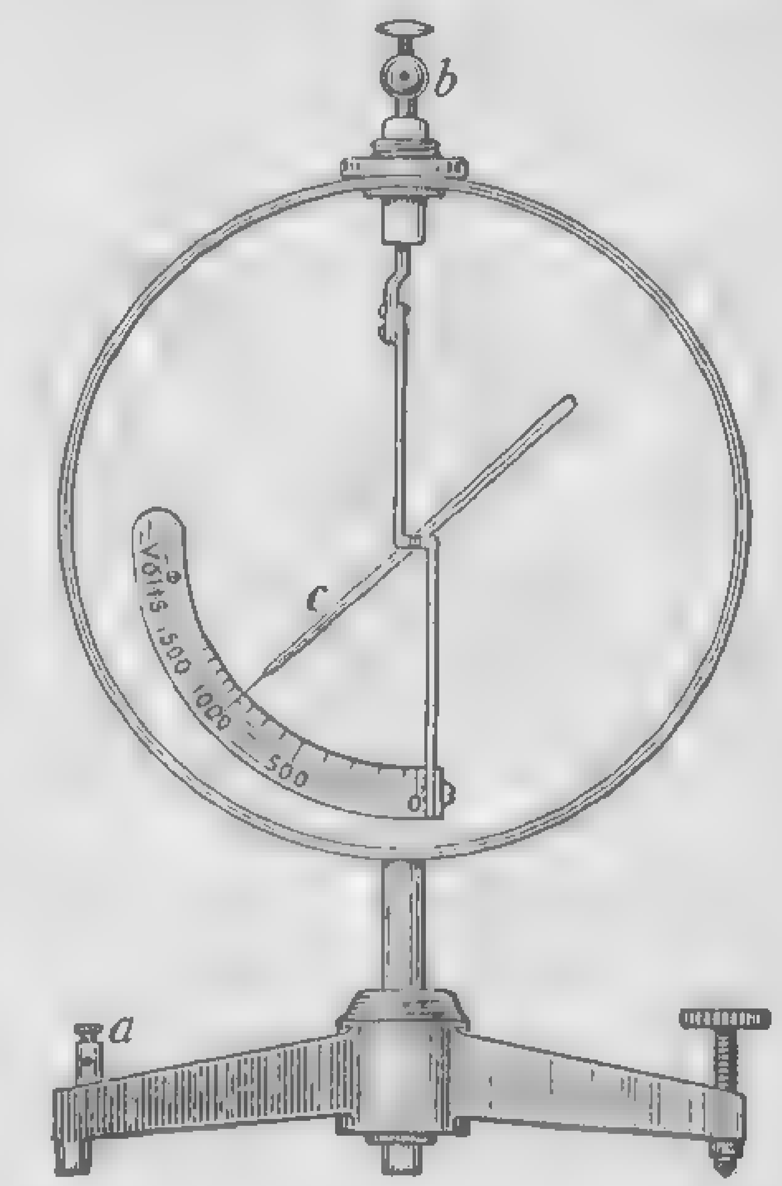


FIG. 238. Electrostatic voltmeter

Since the earth is, on the whole, a good conductor, its potential is everywhere the same (§ 293); hence it makes a convenient standard of reference in potential measurements. To find the potential of a body relative to that of the earth, we connect the outer case of the electroscope to the earth by means of a wire and connect the body to the knob. If the electroscope is calibrated in volts, its reading gives the P.D. between the body and the earth. Such calibrated electroscopes are called *electrostatic voltmeters.* They are the simplest and in many respects the most satisfactory forms of voltmeters to be had. Their use, both in laboratories and in electrical-power plants, is rapidly increasing. They can be made to measure a P.D. as small as $\frac{1}{1000}$ volt and as large as

* If the case is of glass, it should always be made conducting by pasting tinfoil strips on the inside of the jar opposite the leaves and extending these strips over the edge of the jar and down on the outside to the conducting support on which the electroscope rests. The object of this is to maintain the walls always at the potential of the earth.

200,000 volts. Fig. 238 shows one of the simpler forms. The outer case is of metal and is connected to earth at the point *a*. The body whose potential is sought is connected to the knob *b*. This is in metallic contact with the light aluminum vane *c*, which takes the place of the gold leaf.

A very convenient way of measuring a *large* P.D. without a voltmeter is to measure the length of the spark that will pass between the two bodies whose P.D. is sought. The P.D. is roughly proportional to spark length, each centimeter of spark length representing a P.D. of about 30,000 volts if the electrodes are large compared to their distance apart.

295. Condensers. Let a metal plate *A* be mounted on an insulating base and connected with an electroscope, as in Fig. 239. Let a second plate *B* be similarly mounted and connected to earth by a conducting wire. Let *A* be charged and the deflection of the gold leaves noted. If now we push *B* toward *A*, we observe that, as it comes near, the leaves begin to fall together, showing that the potential of *A* is diminished by the presence of *B*, although the quantity of electricity on *A* has remained unchanged. If we convey additional — charges to *A* with the aid of a proof plane, we shall find that many times the original amount of electricity may now be put on *A* before the leaves return to their original divergence; that is, before the body regains its original potential.

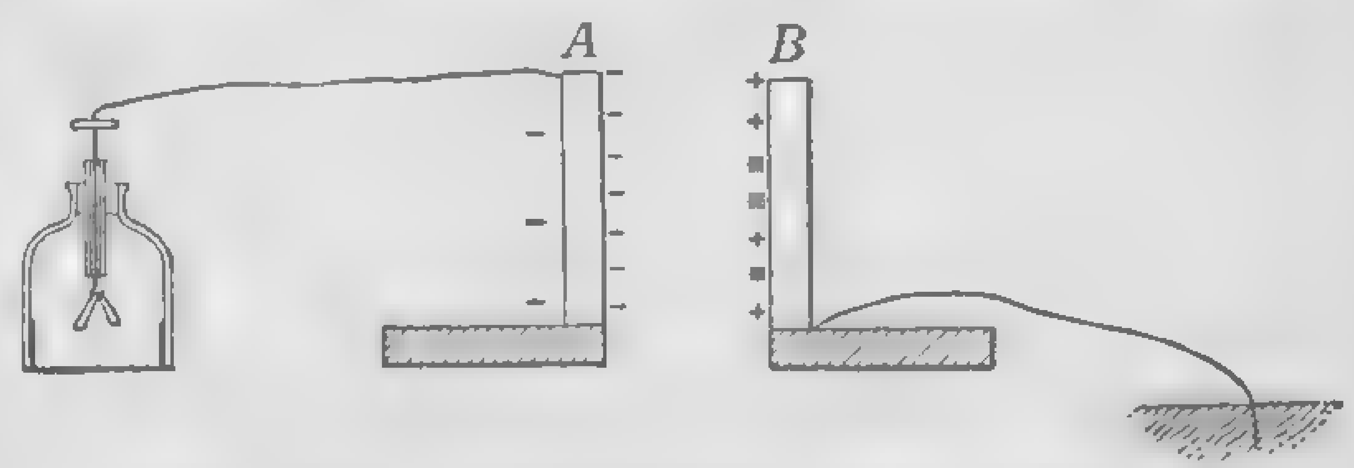


FIG. 239. The principle of the condenser

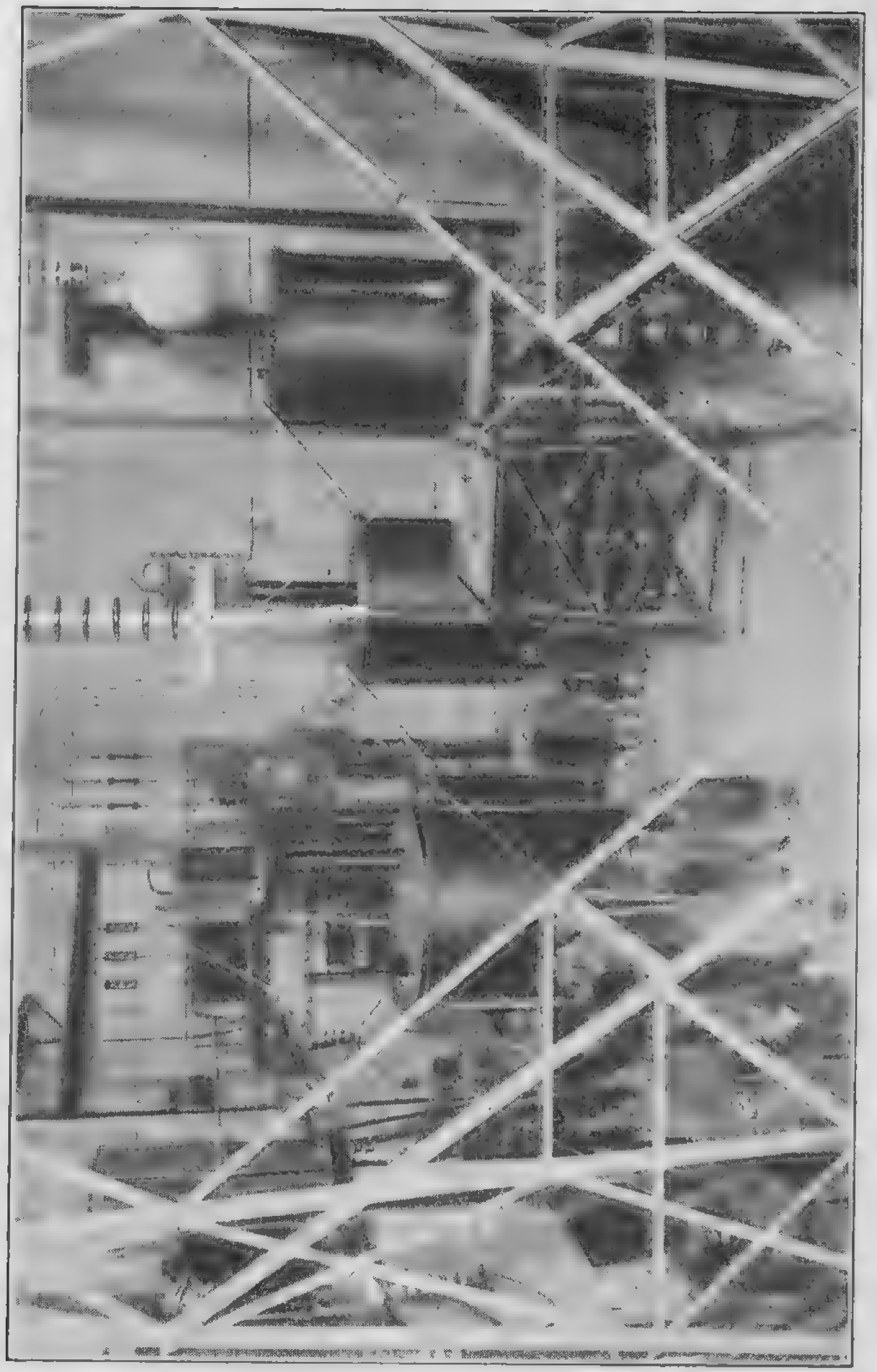
We say, therefore, that the *capacity* of *A* for holding electricity has been very greatly increased by bringing near it another conductor connected to earth. It is evident from this statement that *we measure the capacity of a body by the amount of electricity which must be put upon it to raise the potential a given amount.* The explanation of the increase in capacity in this case is obvious. As soon as *B* was brought near to *A*

NATURAL LIGHTNING

Courtesy of Dr. Arthur S. Brown

MILLION-VOLT ARTIFICIAL LIGHTNING

Ball 1 foot in diameter



A MILLION-VOLT TRANSFORMER

The 1,000,000-volt, 1000-kilowatt laboratory in which the artificial lightning on the preceding page was produced. The million volts to ground is obtained by four 250,000-volt transformers in cascade as shown

it became charged, by induction, with electricity of opposite sign to A, the electricity of like sign to A being driven off to earth through the connecting wire. The attraction between these opposite charges on A and B drew the electricity on A to the face nearest to B and removed it from the more remote parts of A, so that it became possible to put a very much larger charge on A before the tendency of the electricity on A to pass over to the electroscope became as great as it was at first, that is, before the potential of A rose to its initial value. In such a condition the electricity on A is said to be *bound* by the opposite electricity on B.

An arrangement of this sort consisting of two conductors separated by a nonconductor is called a condenser. If the conducting plates are very close together and one of them is grounded, the capacity of the system may be thousands of times as great as that of one of the plates alone.

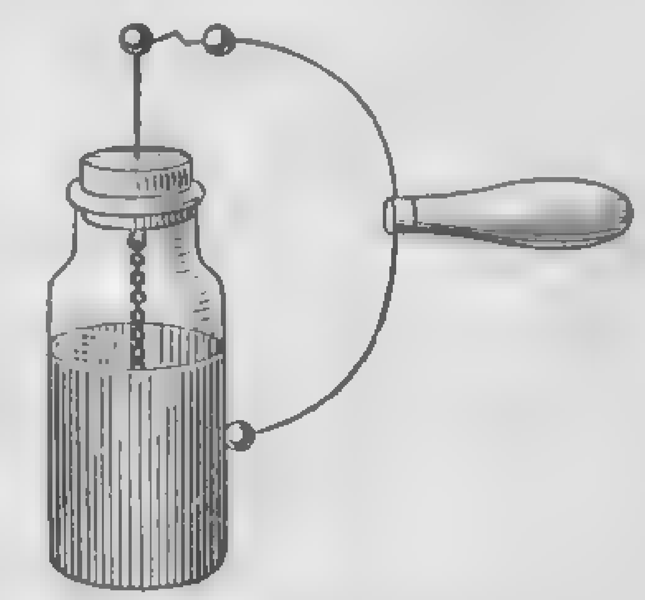


FIG. 240. The Leyden jar

296. The Leyden jar. The most common form of condenser is a glass jar coated part way to the top inside and outside with tin foil (Fig. 240). The inside coating is connected by a chain to the knob, and the outside coating is connected to earth. Condensers of this sort first came into use in Leyden, Holland, in 1745. Hence they are now called *Leyden jars.*

To charge a Leyden jar the outer coating is held in the hand while the knob is brought into contact with one terminal of an electrical machine; for example, the negative. As fast as electrons pass to the knob they spread to the inner coat of the jar, where they repel electrons from the outer coat to the earth, thus leaving it positively charged. If the inner and outer coatings are now connected by a discharging rod, as in Fig. 240, a powerful spark will be produced. This spark is due to the rush of electrons from the − coat to the + coat. Let a charged jar be placed on a glass plate so as to insulate the outer coat. Let the knob be touched with the finger; no appreciable discharge will be noticed. Let the outer coat be in

turn touched with the finger; again no appreciable discharge will appear. But if the inner and outer coatings are connected by the discharger, a powerful spark will pass.

The experiment shows that it is impossible to discharge one side of the jar alone, for practically all the charge is bound by the opposite charge on the other coat. The full discharge can therefore occur only when the inner and outer coats are connected.

Leyden jars and other forms of condensers are of great practical use. They are used, for instance, in certain systems of telephony and telegraphy, in wireless communication, and in electrostatic machines and induction coils. Fig. 241 shows a radio condenser. Its capacity is varied by moving one of its two sets of plates closer to the other or farther from it by a rotary motion.

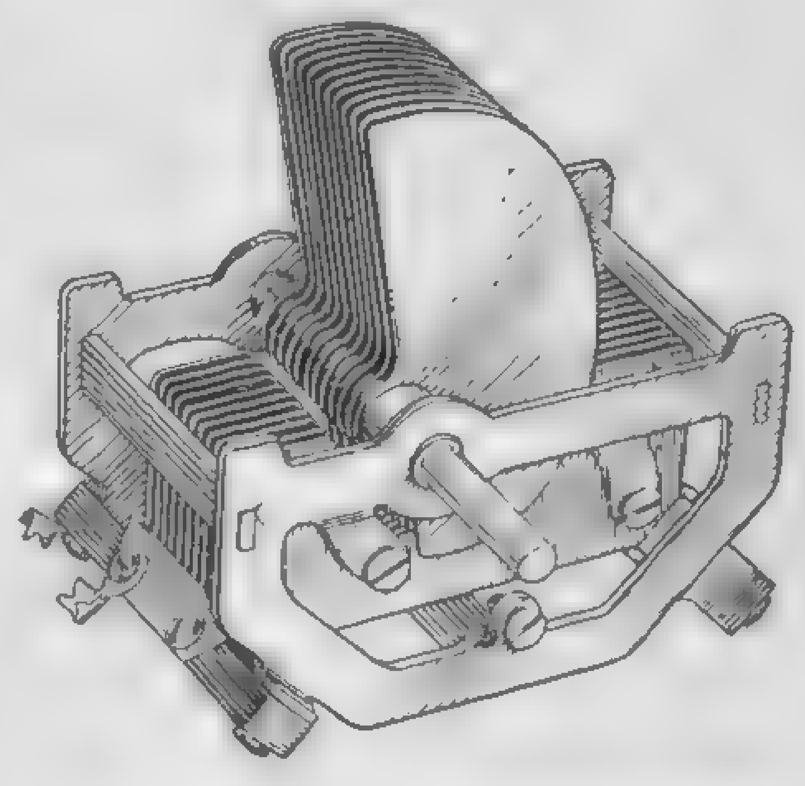


FIG. 241. A variable radio condenser

297. The electrophorus. The electrophorus, a simple electrical generator invented by Volta in 1777, illustrates well the principle underlying the action of all electrostatic machines. All such machines generate electricity primarily by induction, not by friction. *B* (Fig. 242) is a hard-rubber plate which is first charged by rubbing it with fur or flannel. *A* is a metal plate provided with an insulating handle. When the plate *A* is placed upon *B*, touched with the finger, and then removed, it is found possible to draw a spark from it, which in dry weather may be a quarter of an inch or more in length. The process may be repeated an indefinite number of times without producing any diminution in the size of the spark which may be drawn from *A*.

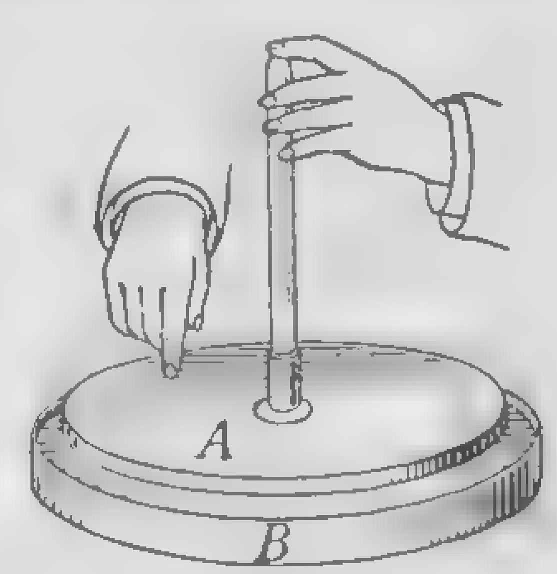


FIG. 242. The electrophorus

If the sign of the charge on *A* is tested by means of an electroscope, it will be found to be positive. This proves

that *A* has been charged by induction, not by contact with *B*, for it is to be remembered that the latter is charged negatively. The reason for this is that even when *A* rests upon *B* it is in reality separated from it, at all but a very few points, by an insulating layer of air; and since *B* is a nonconductor, it cannot appreciably lose its charge by way of these few points of contact. It simply repels negative electrons to the top side of the metal plate *A* and thus charges positively the lower side. The electrons pass off to earth when the plate is touched with the finger. Hence, when the finger is removed and *A* is lifted it possesses a strong positive charge. Every commercial electrostatic machine is simply a continuously acting electrophorus which generates electricity by induction, not by friction.

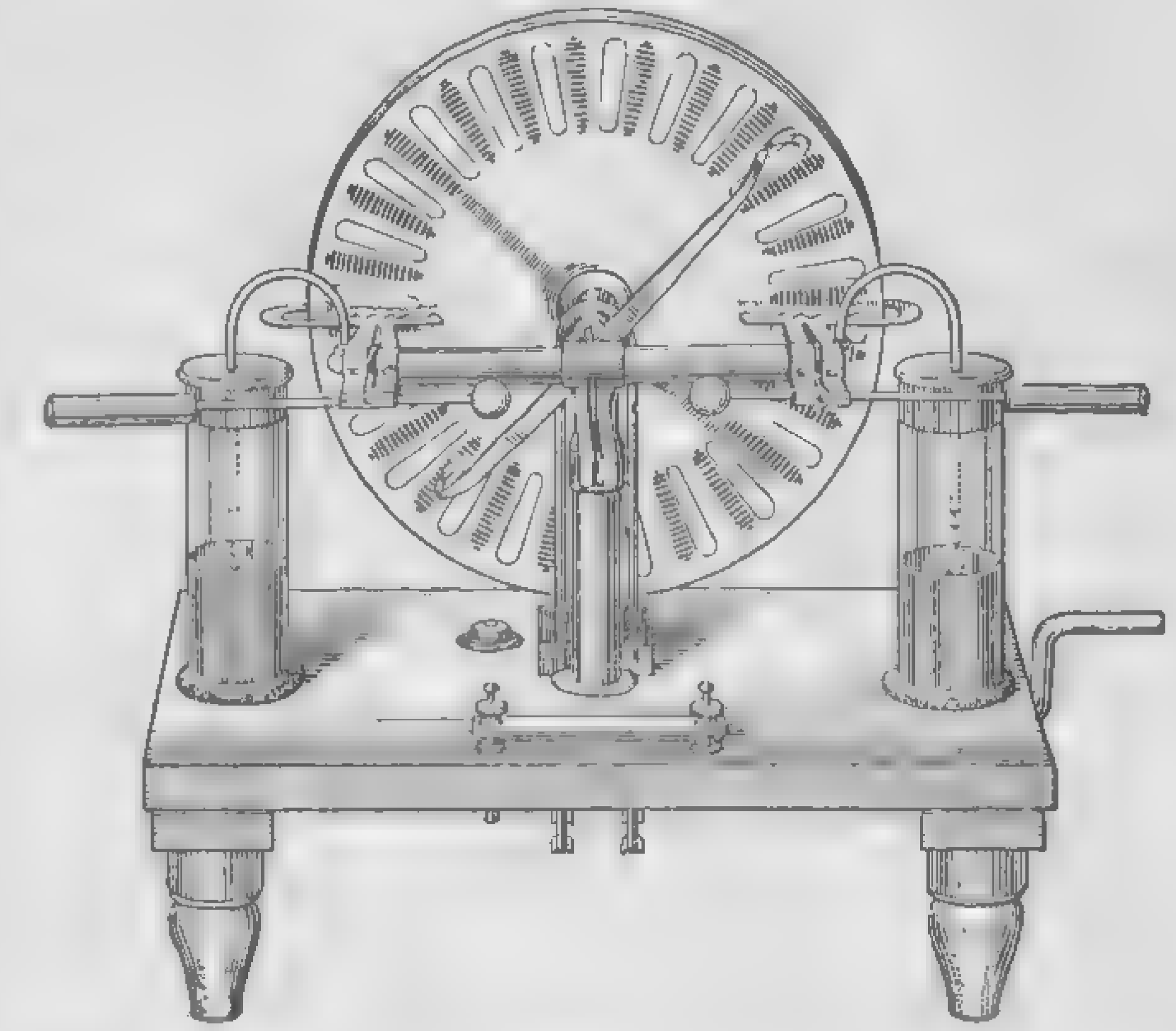


FIG. 243. The Wimshurst induction machine

298. The Wimshurst electrical machine. The ordinary static machine is nothing but a continuously acting electrophorus. Fig. 243 represents the Wimshurst electrical machine. It has two plates revolving in opposite directions, and these plates carry a large number of tinfoil strips which act alternately as inductors and as carriers. The action of the machine may be understood readily from Fig. 244. Suppose that a small negative charge is placed on *a*. This, acting inductively on the rod *rs*, charges *a′* positively. When *a′* in the

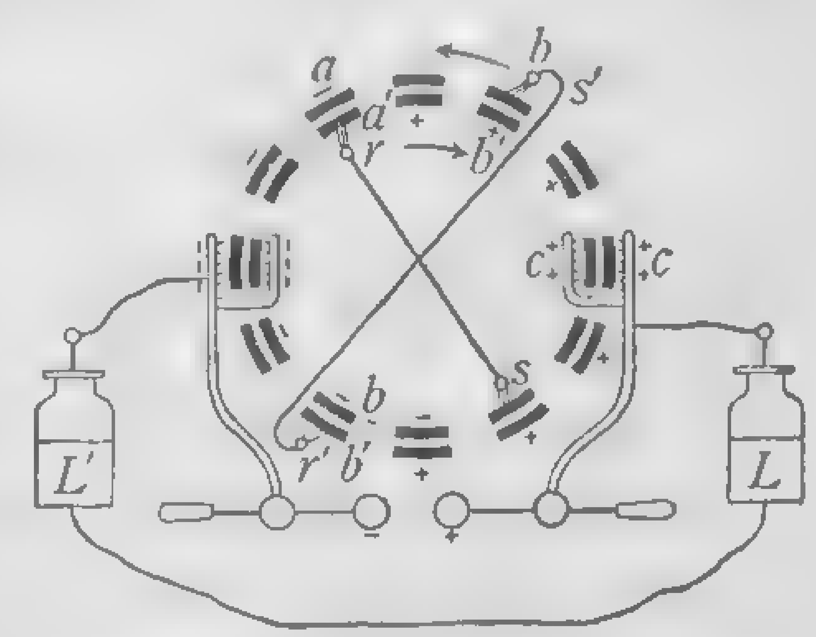


FIG. 244. Principle of Wimshurst machine

course of the rotation reaches the position b', it acts inductively on the rod $s'r'$ and thus charges the disk b negatively. It will be seen that henceforth all the disks in the inner circle receive + charges as they pass the brush r and that all the disks in the outer circle (that is, on the back plate) receive − charges as they pass the brush s'. Similarly, on the lower half of the plates all the disks on the inner circle receive − charges as they pass the brush s, and all the disks on the outer circle receive + charges as they pass the brush r'.

When the positive charges on the inner disks come opposite the combs c, they pass off to the + knob of the machine or to the Leyden jar connected with it. The same process is occurring on the other side, where − charges are being taken off. When a spark passes, the Leyden jars and the connecting system of conductors are restored to their initial conditions, and the process begins again.

SUMMARY. Potential difference bears the same relation to electrical flow as pressure difference to liquid flow.

It may be measured (1) by a calibrated electroscope or electrostatic voltmeter or (2) by the length of the spark discharge.

A condenser consists of two conductors that are separated by a nonconductor.

The capacity of a condenser is the ratio between its charge and the potential difference between its plates.

The electrophorus and the Wimshurst machine are electrostatic generators which depend for their action upon electrostatic induction.

QUESTIONS AND PROBLEMS *

1. Why cannot a Leyden jar be appreciably charged if the outer coat is insulated?

2. If you set a charged Leyden jar on a cake of paraffin, why can you not discharge it by touching one of the coatings?

3. Explain, using a set of drawings, the charging of the cover of an electrophorus.

4. Why is the capacity of a conductor greater when another conductor connected to the earth is near it than when it stands alone?

* Supplementary questions and problems for Chapter XIII are given in the Appendix.

CHAPTER XIV

ELECTRICITY IN MOTION *

DETECTION OF ELECTRIC CURRENTS

299. Electricity in motion produces a magnetic effect. Let a powerfully charged Leyden jar be discharged through a coil which surrounds an unmagnetized knitting needle, insulated by a glass tube, in the manner shown in Fig. 245, the compass needle being at rest in the position shown. After the discharge the knitting needle will be found to be distinctly magnetized. If the sign of the charge on the jar is reversed, the poles of the knitting needle and the direction of deflection of the compass needle will in general be reversed.

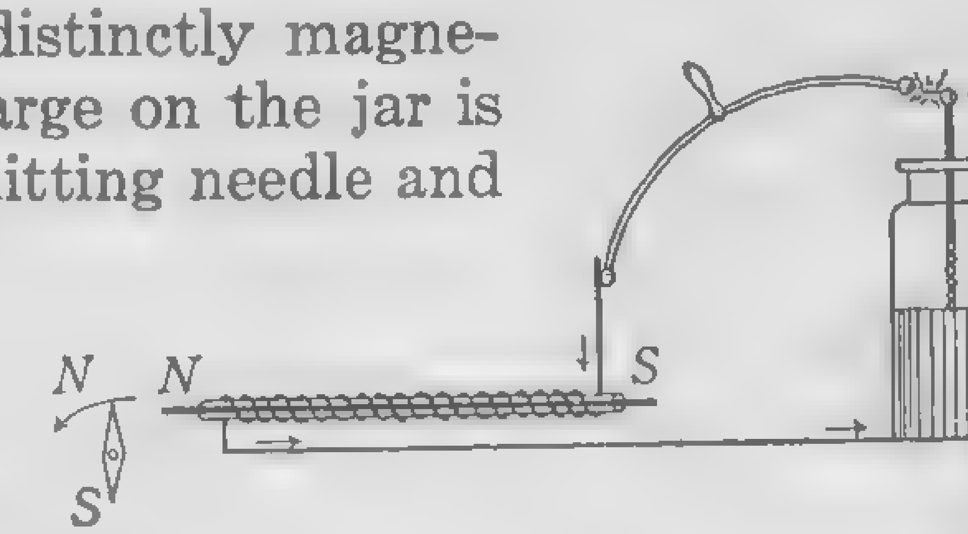


FIG. 245. Magnetic effect of an electric current produced from a static charge

The experiment shows that there is a definite connection between electricity and magnetism. Just what this connection is we do not yet know with certainty, but we do know that magnetic effects are always observable near the path of a moving electrical charge, whereas no such effects can ever be observed near a charge at rest.

Let a charged body be brought near a compass needle. It will attract either end of the needle with equal readiness. While the needle is deflected, insert between it and the charge a sheet of zinc, aluminum, brass, or copper. This will act as an electric screen; that is, it will cut off all effect of the charge. The compass needle will at once swing back to its north-and-south position.

* This chapter should be accompanied or, better, *preceded* by laboratory experiments on the simple cell and on the magnetic effects of a current. See, for example, Experiments 34, 35, 36, 37, and 38 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

Let the compass needle be deflected by a bar magnet, and let the screen be inserted again. The sheet of metal does not cut off the magnetic forces in the slightest degree.

The fact that an electric charge exerts no magnetic force is shown, then, both by the fact that it attracts either end of the compass needle with equal readiness and by the fact that the screen cuts off its action completely, whereas the same screen does not have any effect in cutting off the magnetic force.

An electrical charge in motion is called an electric current, and its presence is most commonly detected by the magnetic effect which it produces. A current of electricity is generally a stream of negative electrons (see Franklin's conception in footnote to § 293, p. 256).

300. The galvanic cell. When a Leyden jar is discharged, only a very small quantity of electricity passes through the connecting wires, since the current lasts for but a small fraction of a second. If we could keep a current flowing continuously through the wire, we should expect the magnetic effect to be much more pronounced. It was in 1786 that Galvani, an Italian anatomist at the University of Bologna, accidentally discovered that there is a chemical method for producing such a continuous current. His discovery was not understood, however, until Volta, while endeavoring to throw light upon it, in 1800 invented an arrangement which is now known sometimes as the *voltaic* and sometimes as the *galvanic* cell. This consists, in its simplest form, of a strip of copper and a strip of zinc immersed in dilute sulphuric acid (Fig. 246).

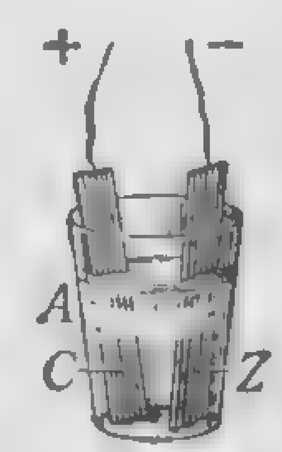


FIG. 246. Simple voltaic cell

Let the terminals of such a cell be connected for a few seconds to the ends of the coil of Fig. 245 when an unmagnetized needle lies within the glass tube. The needle will be found to have become magnetized much more strongly than before. Again, let the wire which connects the terminals of the cell be held above a magnetic needle, as in Fig. 247; the needle will be strongly deflected.

HANS CHRISTIAN OERSTED (1777–1851)

The discoverer of the connection between electricity and magnetism was a Dane and a professor at the University of Copenhagen. His famous experiment made in 1820 stimulated the researches which led to the modern industrial developments of electricity

COUNT ALESSANDRO VOLTA (1745–1827)

Great Italian physicist, professor at Como and at Pavia; inventor of the electroscope, the electrophorus, the condenser, and the voltaic pile (a form of galvanic cell); first measured the potential differences arising from the contact of dissimilar substances; ennobled by Napoleon for his scientific services. The volt, which is the practical unit of potential difference, is named in his honor

ELECTROMAGNETS

This page shows in the upper right-hand corner a photograph of the first electromagnet. It was constructed at Princeton in 1828 by Joseph Henry. He wound the arms of a U-shaped piece of iron with several layers of wire insulated by wrapping around it strips of silk. The main illustration is a huge, modern, lifting magnet which itself weighs 8720 pounds, is 5 feet 2 inches in diameter, and can lift a single flat piece of iron weighing 70,000 pounds. It has 118,000 ampere turns, and carries 84 amperes at 220 volts. The coil is built up of several pancakes of copper straps, the turns of strap being insulated from one another by asbestos ribbon wound between them. The magnet is loading a freight car with pig iron, of which its average lift is 4000 pounds

Evidently, then, the wire which connects the terminals of a galvanic cell carries a current of electricity. Historically the second of these experiments, performed by the Danish physicist Oersted (see opposite page 264) in 1820, preceded the discovery of the magnetizing effects of currents upon needles. It created a great deal of excitement at the time, because it was the first clue which had been found to a relationship between electricity and magnetism.

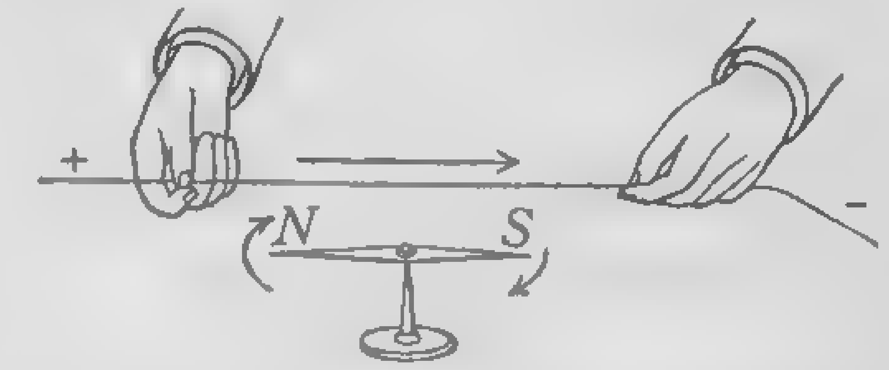


FIG. 247. Oersted's experiment

301. Plates of a galvanic cell are electrically charged. Since an electric current flows through a wire as soon as it is touched to the zinc and copper strips of a galvanic cell, we at once infer that the terminals of such a cell are electrically charged before they are connected. That this is indeed the case may be shown as follows:

Let a metal plate A (Fig. 248), covered with shellac (a nonconductor) on its lower side and provided with an insulating handle, be placed upon a similar plate B which is in contact with the knob of an electroscope. Let the copper plate of a galvanic cell be connected with A and the zinc plate with B, as in Fig. 248. Then let the connecting wires be removed and the plate A lifted away from B. The opposite electrical charges which were bound by their mutual attractions to the adjacent faces of A and B, so long as these faces were separated only by the thin coat of shellac, are freed as soon as A is lifted, and hence part of the charge on B passes to the leaves of the electroscope. These leaves will be seen to diverge. If an ebonite rod which has been rubbed with flannel or cat's fur is brought near the electroscope, the leaves will diverge still farther, thus showing that the zinc plate of the galvanic cell is negatively charged. If the experi-

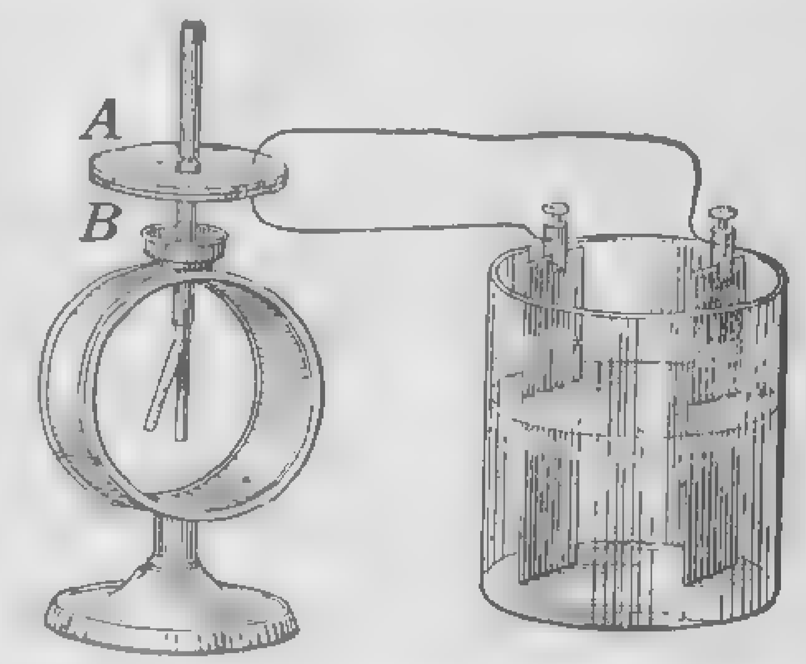


FIG. 248. Showing charges on plates of a voltaic cell

ment is repeated with the copper plate in contact with *B* and the zinc in contact with *A*, the leaves will be found to be positively charged.*

The terminals of a galvanic cell therefore carry positive and negative charges just as do the terminals of an electrical machine in operation. The + charge is always found upon the copper and the − charge upon the zinc. The source of these charges is the chemical action which takes place within the cell. When these terminals are connected by a conductor, a current flows through the latter just as in the case of the electrical machine; and it is the universal custom to consider that a current flows from the positive terminal of a *generator*, or *source* of current, through the external circuit to the negative terminal; that is, in this case, from copper to zinc outside the cell (see § 293 and footnote).

302. Comparison of a galvanic cell and a static machine. If one of the terminals of a galvanic cell is touched directly to the knob of a gold-leaf electroscope, without the use of the condenser plates *A* and *B* of Fig. 248, no divergence of the leaves will be detected; but if one knob of a static machine in operation were so touched, the leaves would probably be torn apart by the violence of the divergence. Since we have seen in § 294 that the divergence of the gold leaves is a measure of the potential of the body to which they are connected, we learn from this experiment that the chemical actions in the galvanic cell are able to produce between its terminals but a very small potential difference in comparison with that produced by the static machine between its terminals. As a matter of fact the potential difference between the terminals of the cell is about one volt, whereas that between the knobs of the electrical machine may be as much as 200,000 volts.

But if the knobs of the static machine are connected to the ends of the wire of Fig. 247, and the machine operated, the current sent through the wire will not be large enough to produce any appreciable effect upon the needle. Since under these same circumstances the galvanic cell produced a very large effect upon the needle, we learn that although the cell develops a very small P.D. between its terminals, it nevertheless sends through the connecting wire very much more electricity per second than the static machine is able to send. This is because the chemical action of the cell is able to recharge the plates to their small P.D. practically as fast as they are discharged through the wire, whereas the static machine requires a relatively long time to recharge its terminals to their high P.D. after they have once been discharged.

* If the deflection of the gold leaves is too small for purposes of demonstration, let a battery of from five to ten cells be used instead of the single cell. If, however, the plates *A* and *B* are three or four inches in diameter, and if their surfaces are very flat, a single cell is sufficient.

SUMMARY. An electrical charge in motion creates a magnetic field about the conductor carrying it.

A galvanic cell, like a static machine, develops + and − charges upon its terminals. The former produces large currents at small potentials; the latter, small currents at high potentials.

QUESTIONS AND PROBLEMS

1. Under what conditions will an electric charge produce a magnetic effect?

2. How can you test whether or not a current is flowing in a wire?

3. How does the current delivered by a cell differ from that delivered by a static machine?

4. Mention three respects in which the behavior of magnets is similar to that of electric charges; two respects in which it is different.

CHEMICAL EFFECTS OF THE CURRENT; ELECTROLYSIS *

303. Electrolysis. Let two platinum electrodes be dipped into a solution of dilute sulphuric acid, and let the terminals of a battery producing a pressure of 10 volts or more be applied to these *electrodes*. Oxygen gas is found to be given off at the electrode at

* This subject should be accompanied or followed by a laboratory experiment on electrolysis and the principle of the storage battery. See, for example, Experiment 44 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

which the current enters the solution, called the *anode* (+), and hydrogen is given off at the electrode at which the current leaves the solution, called the *cathode* (−). These gases may be collected in test tubes in the manner shown in Fig. 249.

When sulphuric acid is mixed with so much water that it forms a dilute solution, the H_2SO_4 molecules split up into three electrically charged parts, called *ions*, the two hydrogen ions each carrying a positive charge and the SO_4 ion carrying a double negative charge (Fig. 250). This phenomenon is known as *dissociation*. The solution as a whole is neutral; that is, it is uncharged, because it contains just as many positive as negative charges.

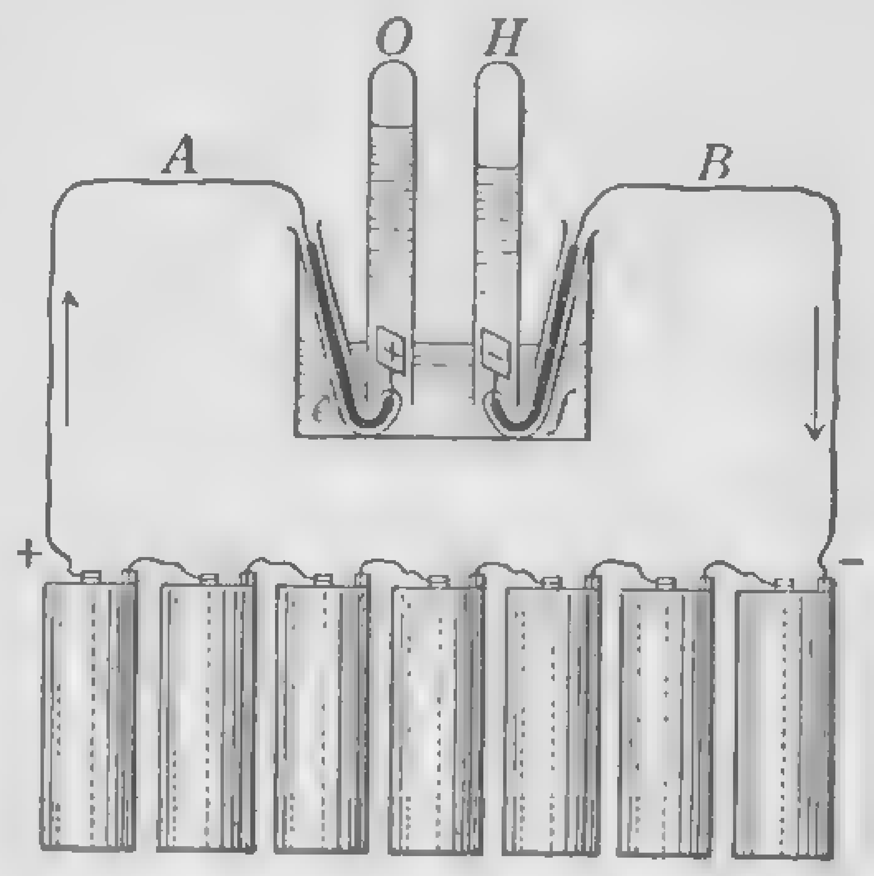


FIG. 249. Electrolysis of water

As soon as an electrical field is established in the solution by connecting the electrodes to the positive and negative terminals of a battery, the hydrogen ions begin to migrate toward the negative electrode (that is, the cathode) and there, after giving up their charges, unite to form molecules of hydrogen gas (Fig. 249). On the other hand, the negative SO_4 ions migrate to the positive electrode (that is, the anode), where they give up their charges to it, and then act upon the water (H_2O), thus forming H_2SO_4 and liberating oxygen.

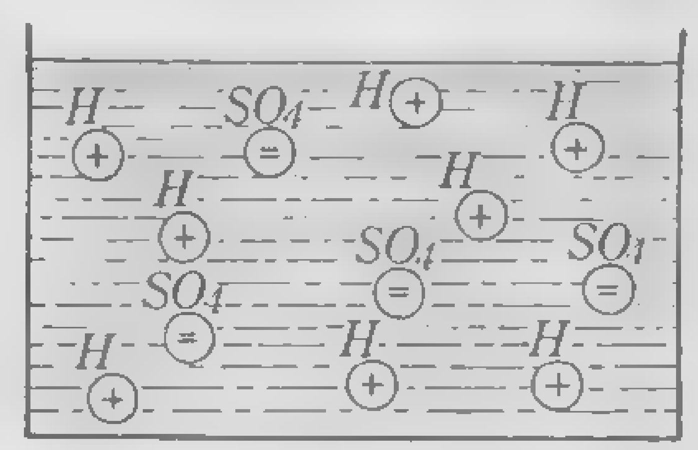


FIG. 250. Showing dissociation of sulphuric acid molecules in water

If the volumes of hydrogen and of oxygen are measured, the hydrogen is found to occupy in every case just twice the volume occupied by the oxygen. This is one of the reasons for believing that a molecule of water consists of two atoms of hydrogen and one of oxygen.

304. Electroplating. If the solution, instead of being sulphuric acid, had been one of copper sulphate ($CuSO_4$), the results would have been precisely the same in every respect, except that, since the hydrogen ions in the solution are now replaced by copper ions, the substance deposited on the cathode is pure copper instead of hydrogen. This is the principle involved in electroplating of all kinds. In commercial work the positive plate, that is, the plate at which the current enters the bath, is always made from the same metal as that which is to be deposited from the solution, for in this case the SO_4 or other negative ions dissolve this plate as fast as the metal ions are deposited upon the other.

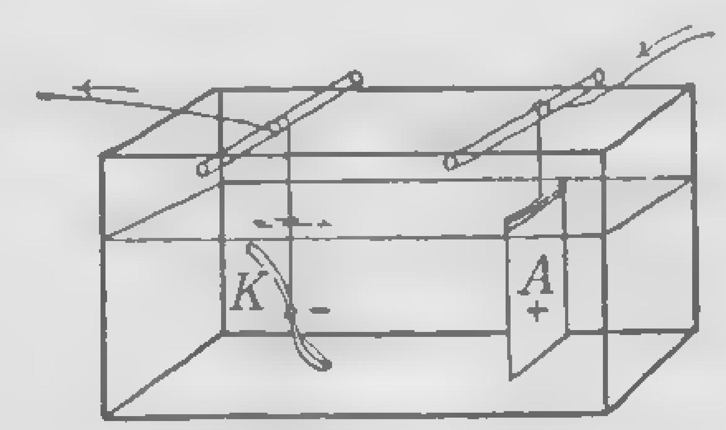


FIG. 251. A simple electroplating bath

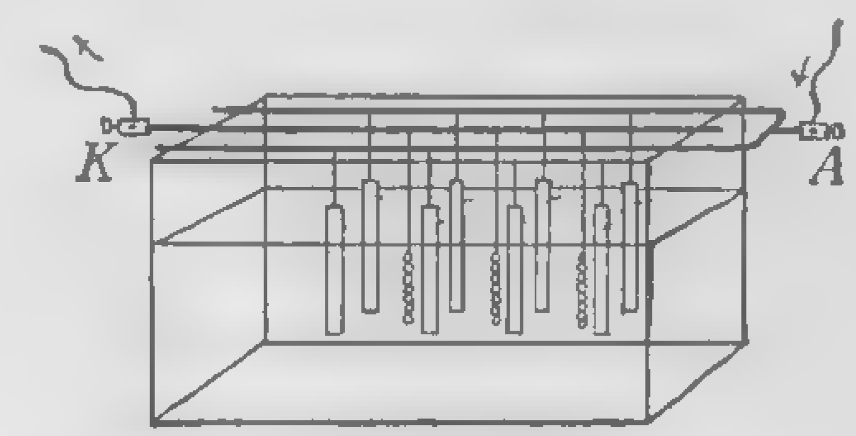


FIG. 252. Electroplating bath

The strength of the solution, therefore, remains unchanged. In effect, the metal is simply taken from one plate and deposited on the other. Fig. 251 represents a simple form of silver-plating bath. The anode *A* is of pure silver. The spoon to be plated is the cathode *K*. In practice the articles to be plated are often suspended from a central rod (Fig. 252), and on both sides about the articles are the suspended anodes. This arrangement gives a more even deposit of metal. In silver plating the solution consists of 500 grams of potassium cyanide and 250 grams of silver cyanide in 10 liters of water.

305. Electrotyping. In the process of electrotyping, the page is first set up in the form of common type. A mold is then taken in wax or gutta-percha. This mold is then coated with powdered graphite to render it a conductor, after which it is ready to be suspended as the cathode in a copper-plating

bath, the anode being a plate of pure copper and the liquid a solution of copper sulphate. When a sheet of copper as thick as a visiting card has been deposited on the mold, the latter is removed and the wax replaced by a type-metal backing, to give rigidity to the copper films. From such a plate as many as a hundred thousand impressions may be made. Nearly all books which run through large editions are printed from such electrotypes.

306. Legal units of current and quantity. In 1834 Faraday (see opposite page 314) found that a given current of electricity flowing for a given time always deposits the same amount of a given element from a solution, whatever be the nature of the solution which contains the element. For example, one ampere, the unit of current, always deposits in an hour 4.025 grams of silver, whether the electrolyte is silver nitrate, silver cyanide, or any other silver compound. This is called the *electrochemical equivalent* of silver. Similarly, an ampere will deposit in an hour 1.181 grams of copper, 1.203 grams of zinc, etc. Faraday further found that the amount of metal deposited in a given cell depended solely on the product of the current strength by the time, that is, on the *quantity* of electricity which had passed through the cell. (When one ampere flows for one hour, the quantity of electricity which passes is sometimes called an *ampere hour.*) These facts are made the basis of the legal definitions of current and quantity, thus:

The unit of current, the ampere, is the current which will deposit .001118 gram of silver in one second.

The unit of quantity, called the coulomb, is the quantity of electricity required to deposit .001118 gram of silver.

SUMMARY. Electrolysis is the passage of current by the process of ion migration.

In electroplating the anode dissolves at the same rate at which the metal is deposited from solution at the cathode.

QUESTIONS AND PROBLEMS

1. Describe and explain the electrolysis of water, covering the following points: (1) ionization of the acid added to the water; (2) material of the anode; (3) electrical state of the anode and the cathode; (4) cause of ion migration; (5) circumstances accompanying the evolution of oxygen.

2. If the terminals of a battery are immersed in a glass of acidulated water, how can you tell from the rate of evolution of the gases at the two electrodes which is positive and which is negative?

3. How could a silver cup be given a gold lining by use of the electric current?

4. How many ampere hours are required to deposit 16.1 g. of silver? How strong was the current that did this, if the deposit occurred in 1 hr.? in 2 hr.? in $\frac{1}{2}$ hr.?

5. If the electrochemical equivalent of silver (expressed as grams per second per ampere) is .001118, how long will it take to deposit 2.4 grams of silver on a spoon if 3 amperes of current are used?

6. What was the strength of a current that deposited 11.84 g. of copper in 30 min.?

7. How many coulombs in an ampere hour?

8. How many ampere hours in a coulomb?

MAGNETIC EFFECTS OF THE CURRENT; PROPERTIES OF COILS

307. Shape of the magnetic field about a current. If we place the wire which connects the plates of a galvanic cell in a vertical position (Fig. 253) and explore with a compass needle the shape of the magnetic field about the current, we find that the magnetic lines are concentric circles lying in a plane perpendicular to the wire and having the wire as their common center. We find, moreover, that reversing the current reverses the direction of the needle. If the current is very strong (say 40 amperes), this shape of the field can be shown by scattering iron filings on a plate through which the current passes (Fig. 253). If the current is weak, the experiment should be performed by using a large number of turns of wire, as indicated in Fig. 254.

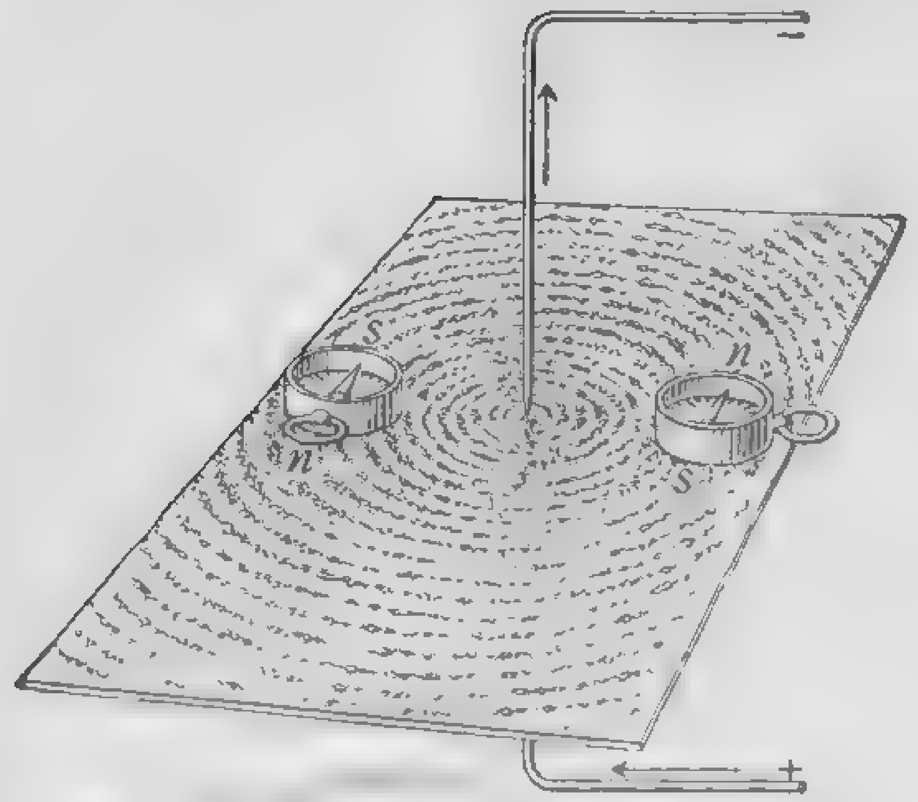


FIG. 253

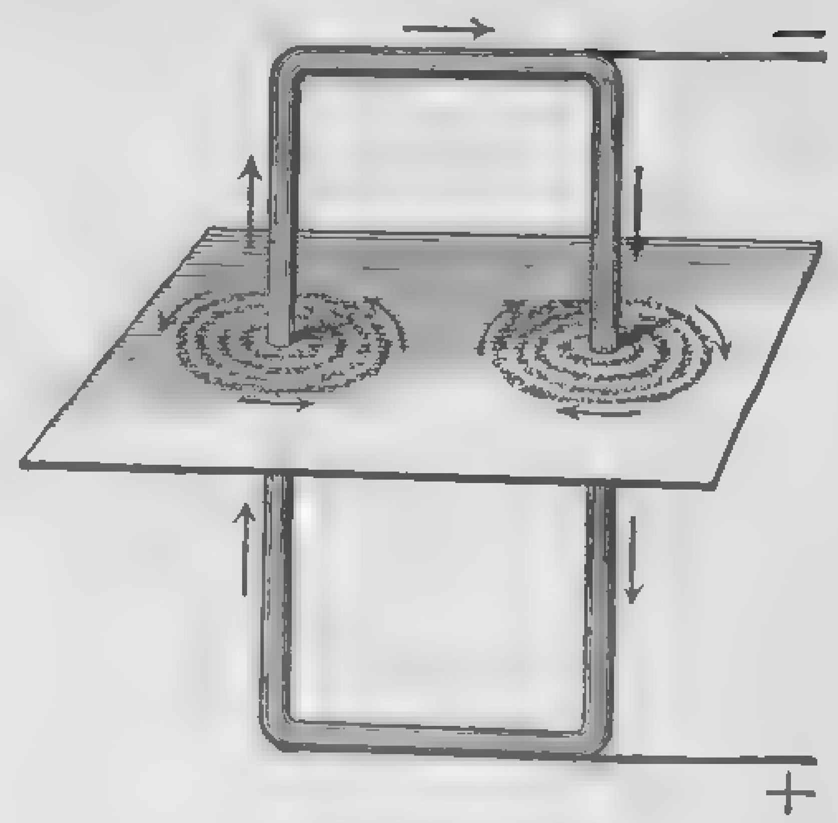


FIG. 254

Magnetic field about a current

The relation between the direction in which the current flows and the direction in which the *N* pole of the needle points (this is, by definition, the direction of the magnetic field) is given in the following convenient rule, known as Ampère's rule: *If the right hand grasps the wire as in Fig. 255 so that the thumb points in the direction in which the current is flowing, then the magnetic lines encircle the wire in the same direction as do the fingers of the hand.*

FIG. 255. The right-hand rule

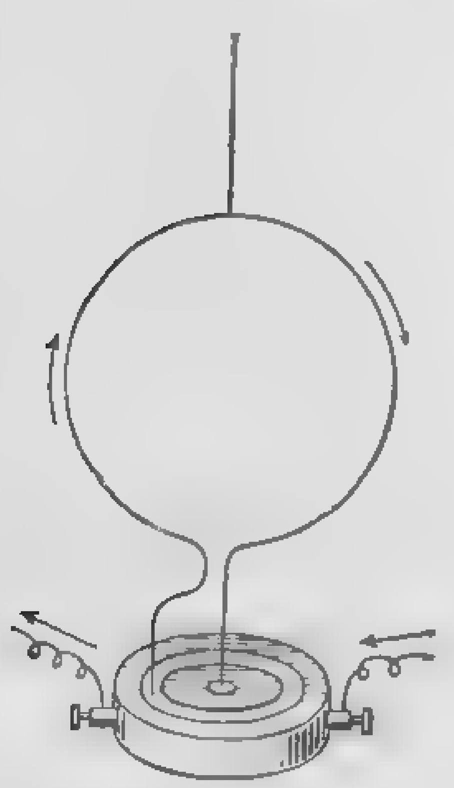


FIG. 256. A loop equivalent to a flat magnetic disk

308. Loop of wire carrying a current equivalent to a magnet disk. Let a single loop of wire be suspended from a thread in the manner shown in Fig. 256, so that its ends dip into two mercury cups. Then let the current from three or four dry cells be sent through the loop. The latter will be found slowly to set itself so that the face of the loop from which the magnetic lines emerge, as given by the right-hand rule (see § 307 and also Fig. 257), is toward the north. Let a bar magnet be brought near

the loop. The latter will be found to behave toward the magnet in all respects as though it were a flat magnetic disk whose boundary is the wire, the face which turns toward the north being an *N* pole and the other an *S* pole.

The experiment shows what position a loop bearing a current will always tend to assume in a magnetic field; for, since a magnet will always tend to set itself so that the line connecting its poles is parallel to the direction of the magnetic lines of the field in which it is placed, a loop must set itself so that a line connecting its magnetic poles is parallel to the lines of the magnetic field, that is, so that *the plane of the loop is perpendicular to the field* (see Fig. 258); or, to state the same thing in slightly different form, *if a loop of wire, free to turn, is carrying a current in a magnetic field, the loop will set itself so as to include as many as possible of the lines of force of the field.*

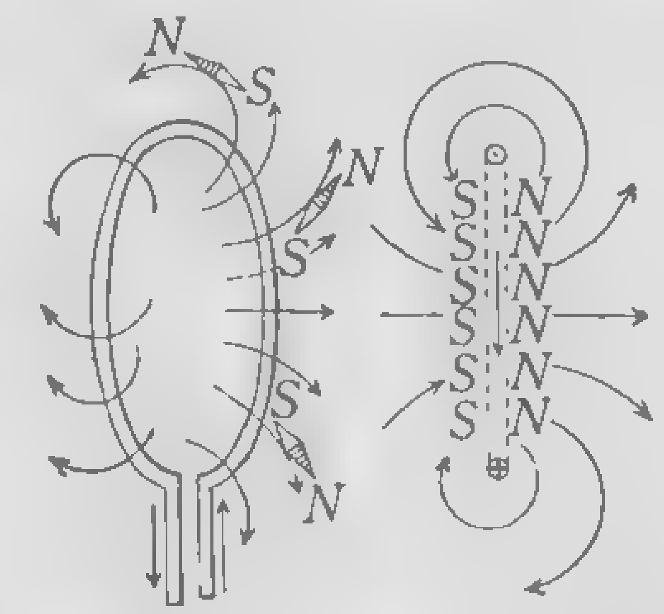


FIG. 257. North pole of disk is face from which magnetic lines emerge; south pole is face into which they enter

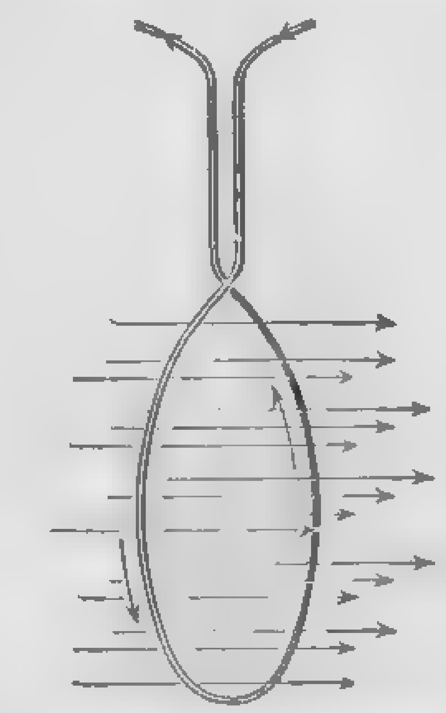


FIG. 258. Position assumed by a loop carrying a current in a magnetic field

309. Helix carrying a current equivalent to a bar magnet. Let a wire bearing a current be wound into a series of loops (a *helix*) and held near a suspended magnet, as in Fig. 259. It will be found to act in every respect like a magnet, with an *N* pole at one end and an *S* pole at the other.

This result might have been predicted from the fact that a single loop is equivalent to a flat-disk magnet; for when such disks are placed side by side in a series, as in the helix, the result must be the same as placing a series of disk magnets in a row, the *N* pole of one being directly in contact with the

S pole of the next, etc. These poles would therefore all neutralize each other except at the two ends. We therefore get a magnetic field of the shape shown in Fig. 260, the direction of the arrows representing as usual the direction in which an *N* pole tends to move.

The right-hand rule as given in § 307 is sufficient in every case to determine which is the *N* and which the *S* pole of a

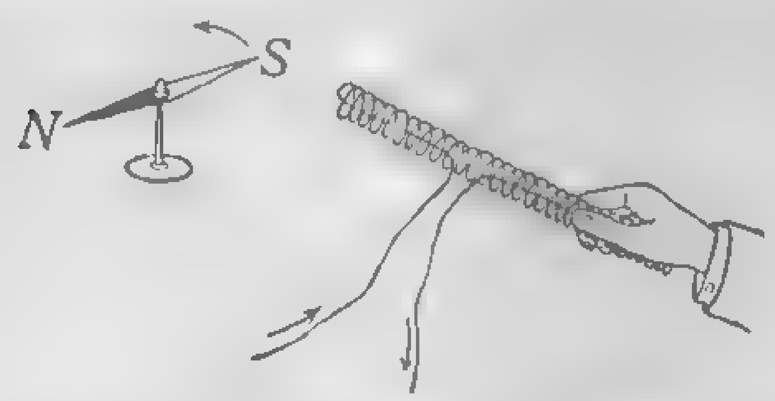


FIG. 259. Magnetic effect of a helix

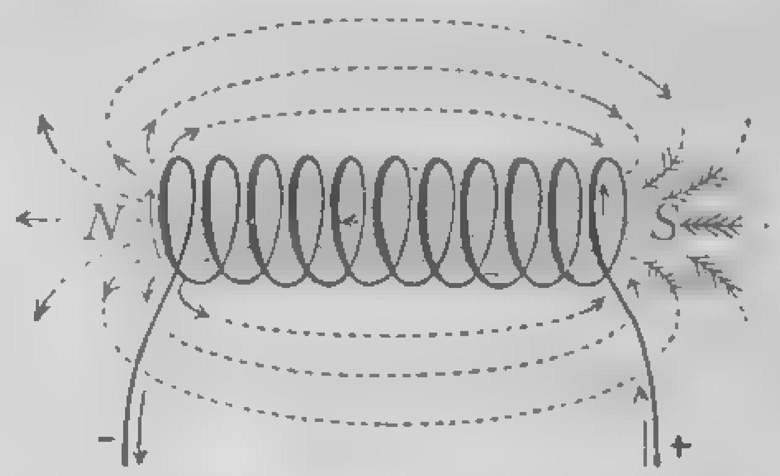


FIG. 260. Magnetic field of helix

helix, that is, from which end the lines of magnetic force emerge from the helix and at which end they enter it. But it is found convenient, in the consideration of coils, to restate the right-hand rule in a slightly different way, thus: *If the coil is grasped in the right hand in such a way that the fingers point in the direction in which the current is flowing in the wires, the thumb will point in the direction of the north pole of the helix* (see Fig. 261). Similarly, if the sign of the poles is known, but the direction of the current unknown, it may be determined as follows: *If the right hand is placed against the coil with the thumb pointing in the direction of the lines of force* (that is, toward the north pole of the helix), *the fingers will pass around the coil in the direction in which the current is flowing.*

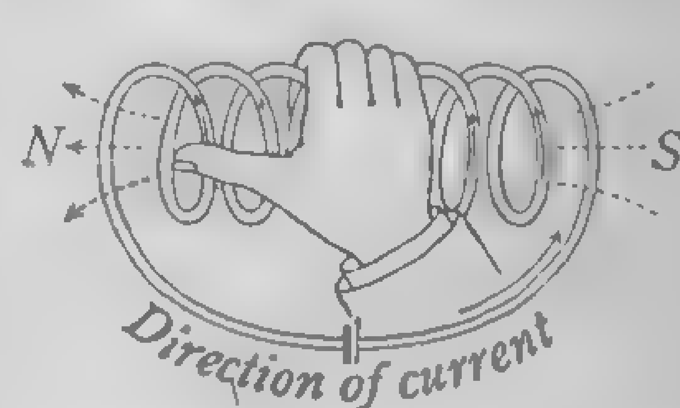


FIG. 261. Rule for poles of helix

310. The electromagnet. Let a core of soft iron be inserted in the helix (Fig. 262). The poles will be found to be enormously stronger than before. This is because the core is magnetized by induction from the field of the helix in precisely the same way in

which it would be magnetized by induction if placed in the field of a permanent magnet. The new field strength about the coil is now the sum of the fields due to the core and that due to the coil. If the current is broken, the core will at once lose the greater part of its magnetism. If the current is reversed, the polarity of the core will be reversed. Such a coil with a soft-iron core is called an *electromagnet.*

The strength of an electromagnet can be very greatly increased by giving it such form that the magnetic lines can

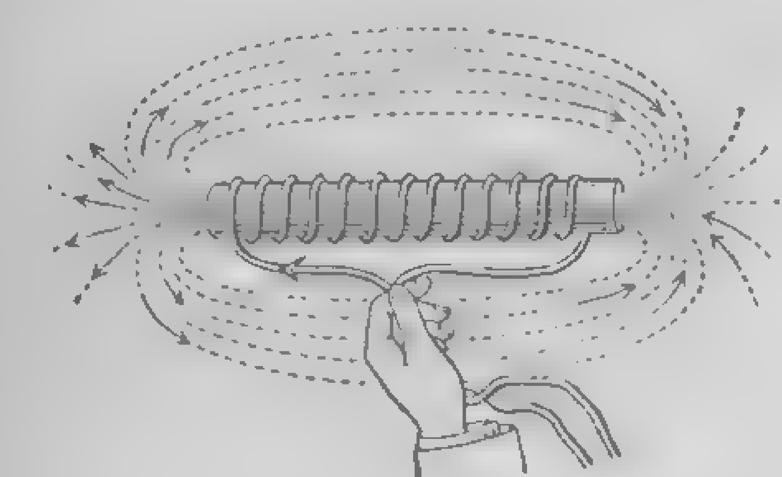


FIG. 262. The bar electromagnet

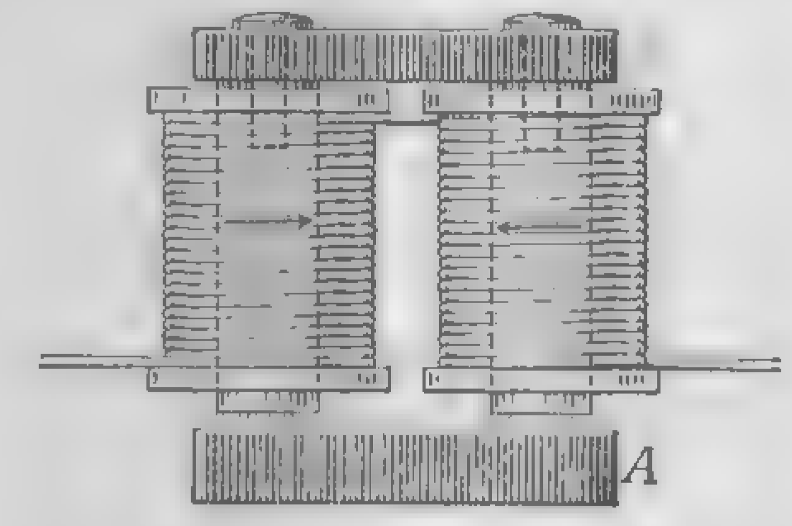


FIG. 263. The horseshoe electromagnet

remain in iron throughout their entire length instead of emerging into air, as they do in Fig. 262. For this reason electromagnets are usually built in the horseshoe form and provided with an armature *A* (Fig. 263), through which a complete iron path for the lines of force is established, as shown in Fig. 264. The strength of such a magnet depends upon the quantity and quality and form of the iron, but chiefly upon the number of *ampere turns* which encircle it, the expression "ampere turns" denoting the product of the number of turns of wire about the magnet by the number of amperes flowing in each turn. Thus, a current of $\frac{1}{100}$ ampere flowing 1000 times around a core will make an electromagnet of precisely the same strength as a current of 1 ampere flowing 10 times about the core. (See modern lifting magnet opposite page 265.)

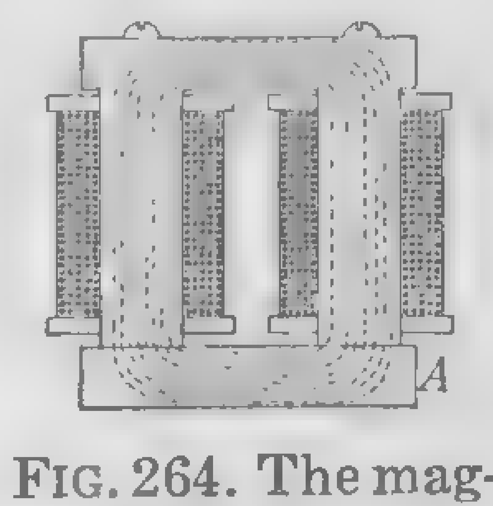


FIG. 264. The magnetic circuit of an electromagnet

SUMMARY. *Right-hand rules.* (1) Grasp a conductor with the right hand, the thumb pointing in the direction of the current; the fingers then point along the magnetic lines of force. (2) Grasp a helix with the right hand so that the fingers point in the direction of the current in the coils; the thumb then points in the direction of the magnetic lines.

The strength of an electromagnet depends chiefly upon the number of its ampere turns.

QUESTIONS AND PROBLEMS

1. In what direction will the north pole of a magnetic needle be deflected if it is held above a current flowing from north to south?

2. A man stands beneath a north-and-south trolley line and finds that a magnetic needle in his hand has its north pole deflected toward the east. What is the direction of the current flowing in the wire?

3. Why would an electromagnet made by winding bare wire on a bare iron core be worthless as a magnet?

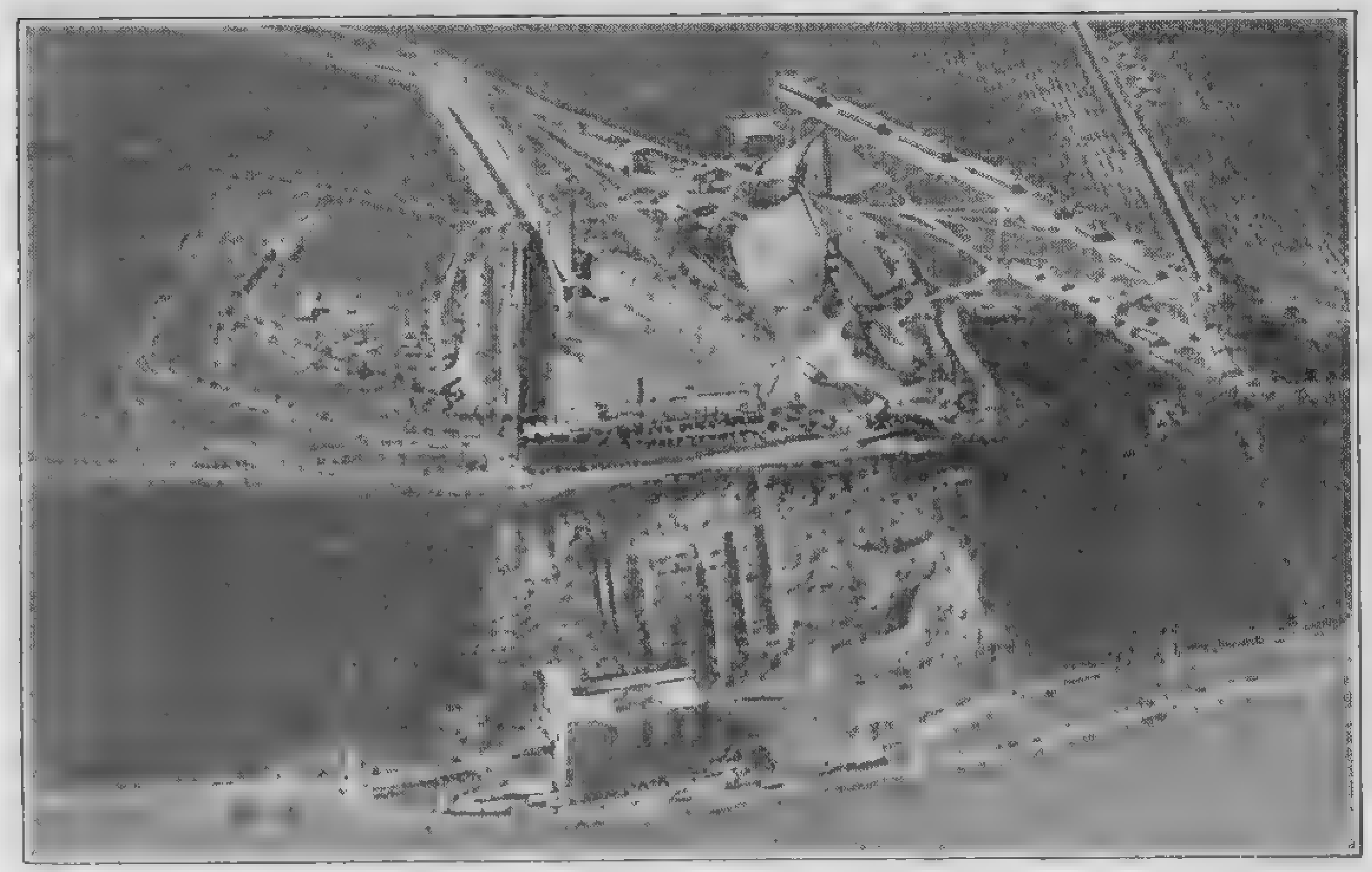
4. If one looks down on the ends of a U-shaped electromagnet, does the current encircle the two coils in the same or in opposite directions? Does it run clockwise or counterclockwise about the *N* pole?

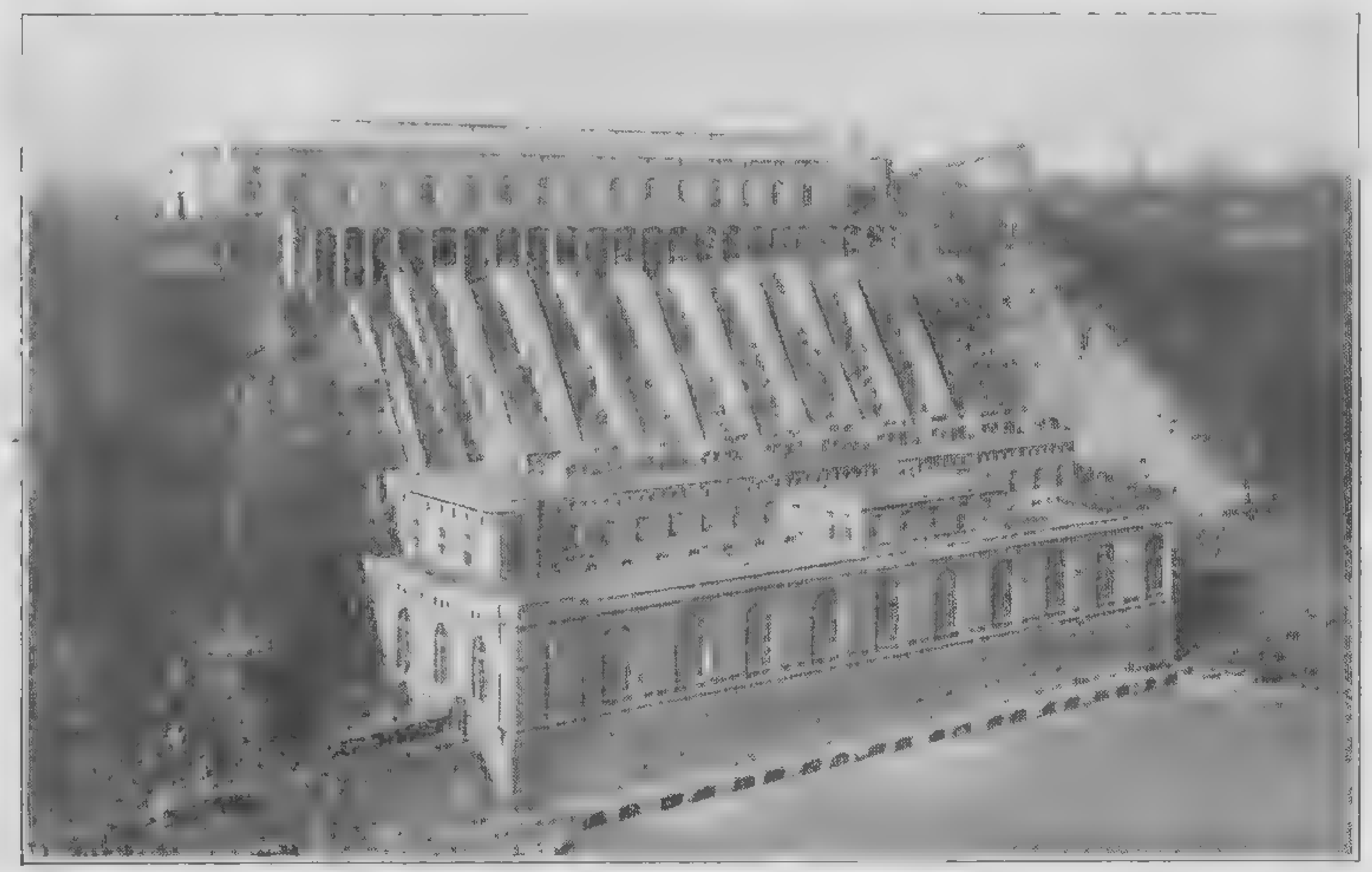
5. The plane of a suspended loop of wire is east and west. A current is sent through it, passing from east to west on the upper side. What will happen to the loop if it is perfectly free to turn?

6. Two electromagnets have identical cores. One is wound with 5000 turns of fine wire and carries .04 ampere; the other is wound with 100 turns of thicker wire. How many amperes must flow through the 100-turn helix to produce the same magnetic effect in the core?

MEASUREMENT OF ELECTRIC CURRENTS

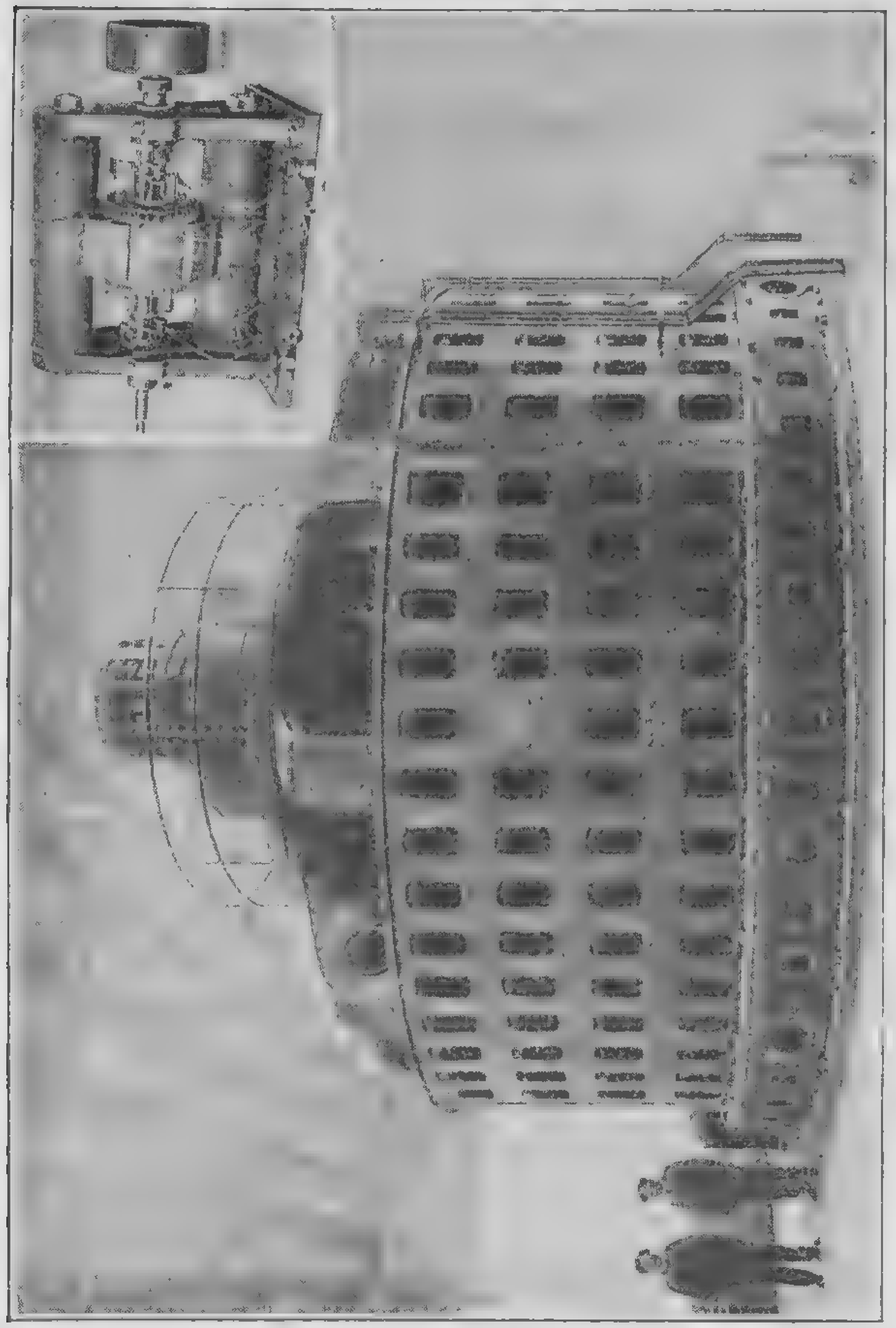
311. The galvanometer. Electric currents are, in general, measured by the strength of the magnetic effect which they are able to produce under specific conditions. Thus, if the wire carrying a current is wound into circular form, as in





MAGNIFICENT HALF-MILLION-HORSE-POWER HYDROELECTRIC STATION AT QUEENSTON, CANADA

The upper picture shows the station in construction with the $12\frac{3}{4}$-mile canal and partly blasted rock for penstocks. The lower picture shows the completed plant. Water drops 305 feet to turbines, which abstract its energy almost completely, as shown by the quietness of water from the tail race. (Courtesy of the Hydroelectric Power Commission of Ontario, Canada)



EARLIEST AND LATEST FORMS OF DYNAMOS BUILT IN THE UNITED STATES

The dynamo in the upper right-hand corner is the first built in the United States (a 3-kilowatt, 150-volt replica by Cornell students in 1875 of the original Gramme dynamo built in France in 1873). The other dynamo is one of three huge, 65,000-kilowatt, 12,000-volt, turbine-driven generators recently installed at Niagara Falls. The one machine is 26 inches high; the other 26 feet. (Courtesy of the General Electric Company)

Fig. 265, the right-hand rule shows us that the shape of the magnetic field at the center of the coil is similar to that shown in the figure. If, then, the coil is placed in a north-and-south plane and a compass needle is placed at the center, the passage of the current through the coil tends to deflect the needle so as to make it point east and west. The amount of deflection under these conditions is taken as the measure of current strength. The unit of current, the *ampere*, is in fact approximately the same as the current which, flowing through a circular coil of three turns and 10 centimeters radius, set in a north-and-south plane, will produce a deflection of 45 degrees at Washington in a small compass needle placed at its center. The legal definition of the ampere is, however, based on the chemical effect of a current. It was given in § 306.

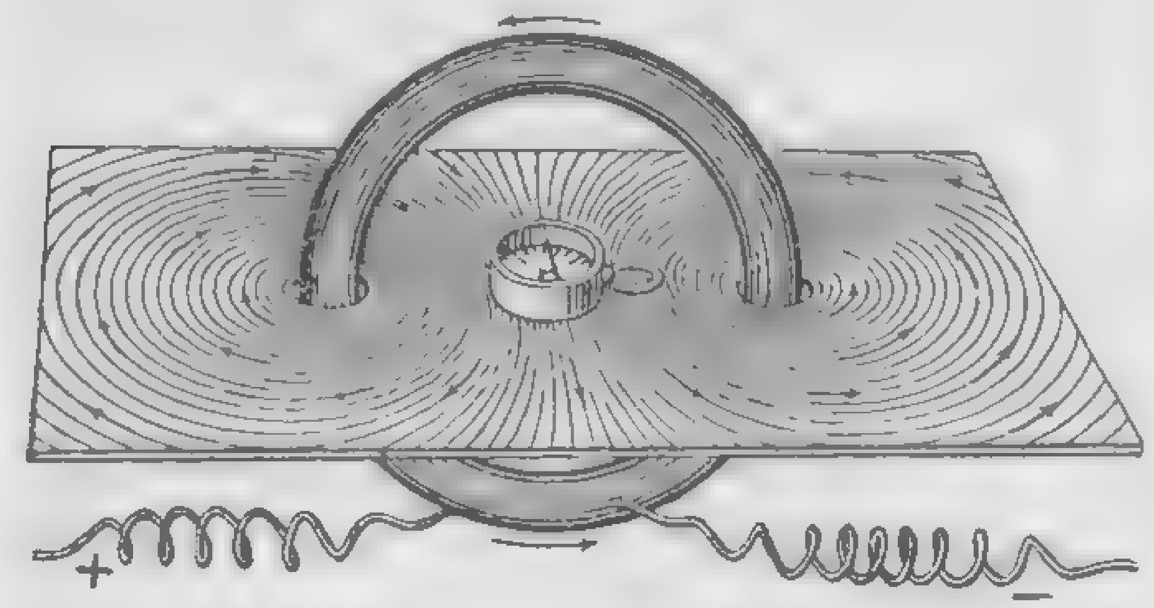


FIG. 265. Magnetic field about a circular coil carrying a current

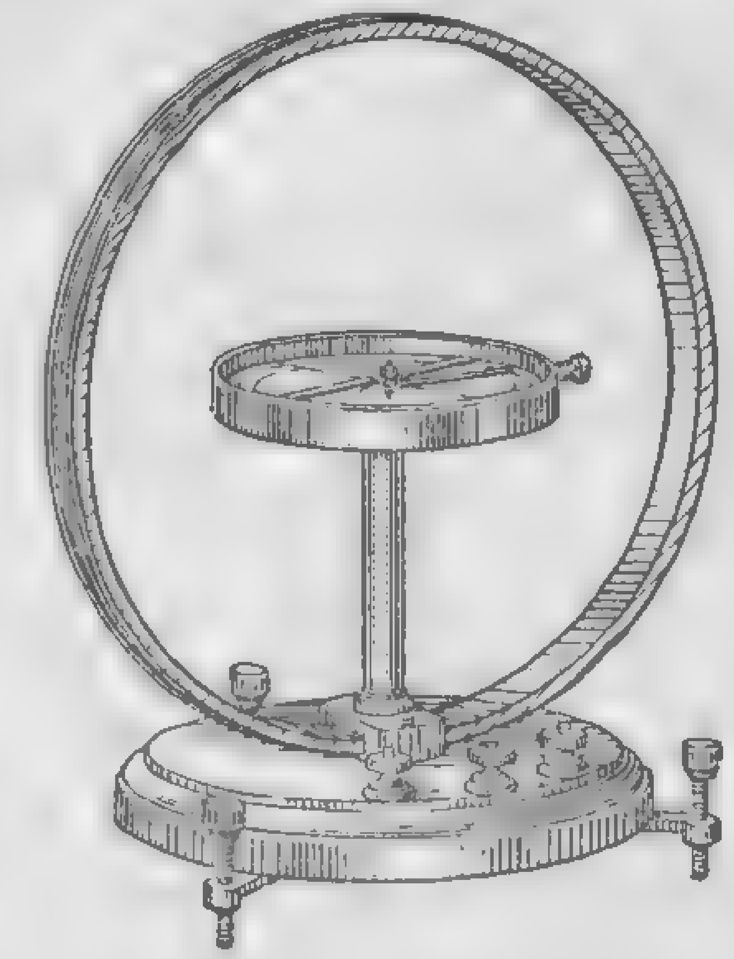


FIG. 266. A fixed-coil galvanometer

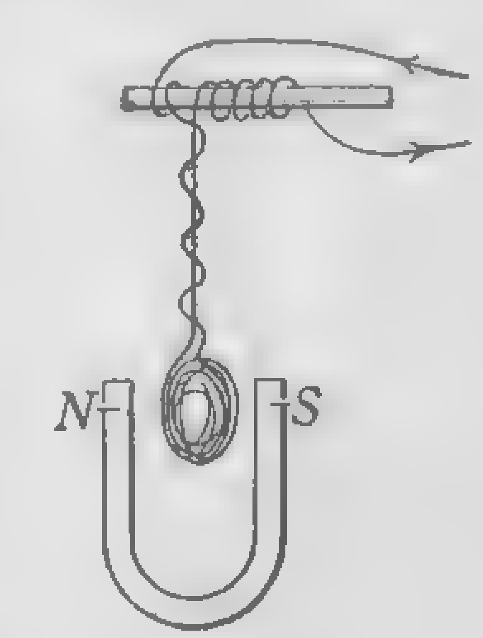


FIG. 267. Simple suspended-coil galvanometer

Nearly all current-measuring instruments consist essentially either of a small compass needle at the center of a fixed coil, as in Fig. 266, or of a movable coil suspended between the poles of a fixed magnet in the manner illustrated roughly in Fig. 267. The passage of the current through the coil produces a deflection, in the

first case, of the magnetic needle with reference to the fixed coil, and, in the second case, of the coil with reference to the fixed magnet. If the instrument has been calibrated to give the strength of the current directly in amperes, it is called an *ammeter*; otherwise, a *galvanometer* (Fig. 268).

312. The commercial ammeter. Fig. 269 shows the construction of the usual form of commercial ammeter. The

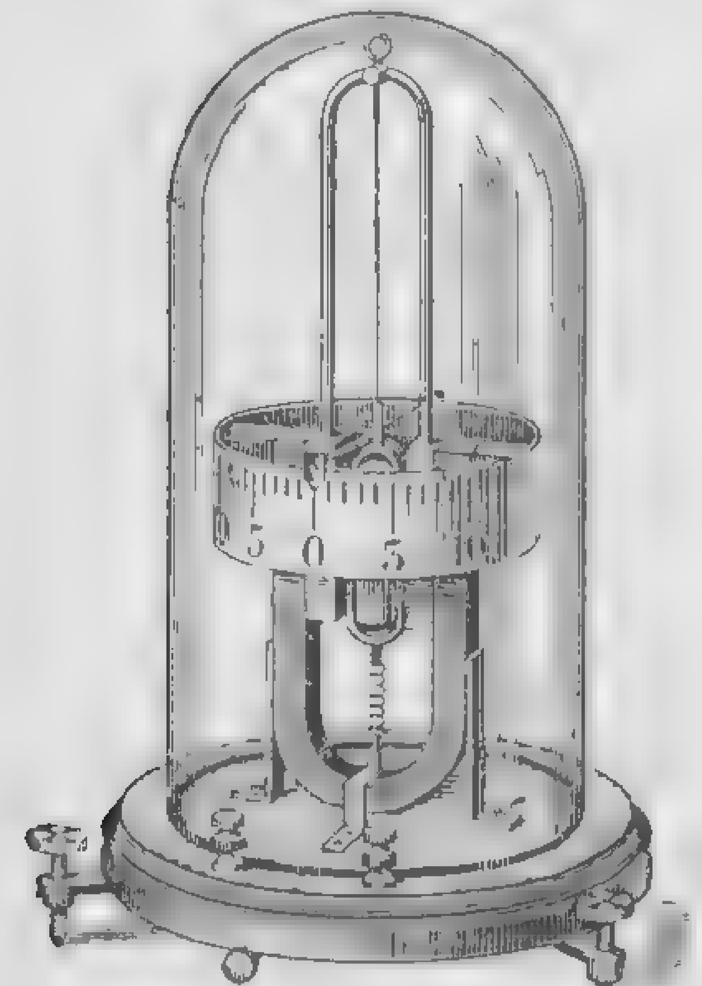


FIG. 268. A lecture-table galvanometer

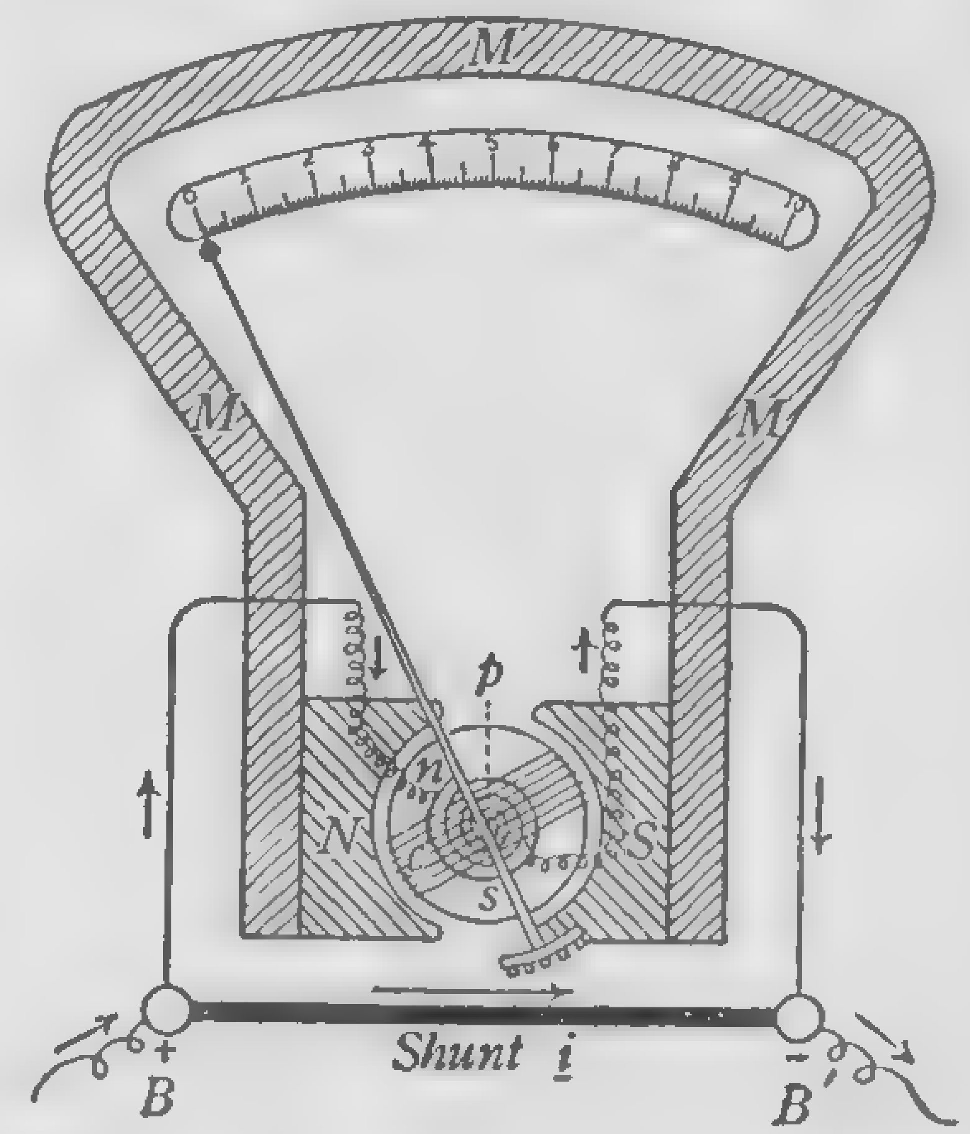


FIG. 269. Construction of a commercial ammeter

coil c is pivoted on jewel bearings and is held at its zero position by a spiral spring p. It loosely surrounds and freely turns about a cylindrical mass of soft iron. When a current flows through the instrument, if it were not for the spring p the coil would turn through about 120°, or until its N pole came opposite the S pole of the magnet (see Fig. 269). This zero position of the coil is chosen because it enables the scale divisions to be nearly equal. The conductor i, called a *shunt*, carries nearly all the current that enters the instrument at B, only an *exceedingly small* portion of it going through the moving coil c. The shunt is usually placed inside the instrument unless interchangeable shunts are desired.

SUMMARY. Currents are usually measured with galvanometers. These may have either (1) a movable coil with a stationary magnet or (2) a movable magnet with a stationary coil.

QUESTIONS AND PROBLEMS

1. What is the principle involved in the chemical method of measuring the strength of an electric current? in the magnetic method?

2. How could you test whether or not the strength of an electric current is the same in all parts of a circuit? Try it.

3. Explain from the diagram of the commercial ammeter (Fig. 269) the principle of the suspended-coil, or d'Arsonval, type of galvanometer.

4. In a galvanometer consisting of a stationary coil and a magnetic compass, what force opposes the motion due to the magnetic field of the current?

5. What force acts to oppose the motion of the coil (1) in the suspended-coil galvanometer; (2) in the commercial ammeter represented in Fig. 269?

6. In calibrating an ammeter the current which produces a certain deflection is found to deposit $\frac{1}{2}$ g. of silver in 50 min. What is the strength of the current?

ELECTRIC BELL AND TELEGRAPH

313. The electric bell. The electric bell (Fig. 270) is one of the simplest applications of the electromagnet. When the button P is pressed (Figs. 270 and 271), the electric circuit of the battery is closed, and a current flows in at A, through the coils of the magnet, over the closed contact c, and out again at B. But as soon as this current is established, the electromagnet E pulls over the armature a, and in so doing breaks the contact at c. This stops the current and demagnetizes the magnet E. The armature is then thrown back against c by the elasticity of the spring s which supports it. No sooner is the contact made at c than the current again begins to flow and the former operation is repeated. Thus the circuit is automatically made and broken at c, and the hammer H is in consequence set into rapid vibration against the rim of the bell.

314. The telegraph. The electric telegraph is another simple application of the electromagnet. The principle is illustrated in Fig. 272. As soon as the key *K*, at Chicago for example, is closed, the current flows over the line to, we will say, New York. There it passes through the electromagnet *m*, and thence back to Chicago through the earth. The armature *b* is held down by

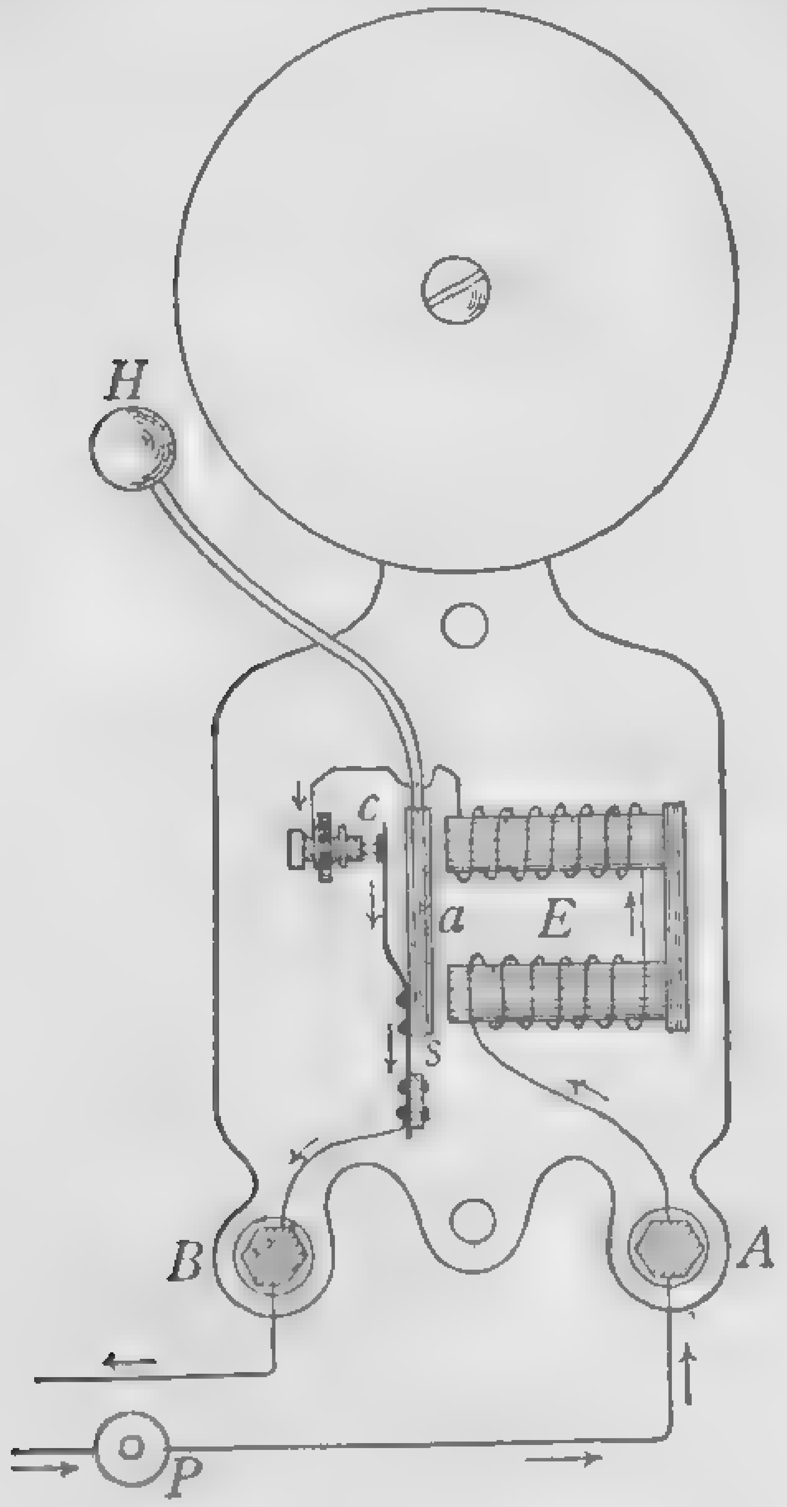


FIG. 270. The electric bell

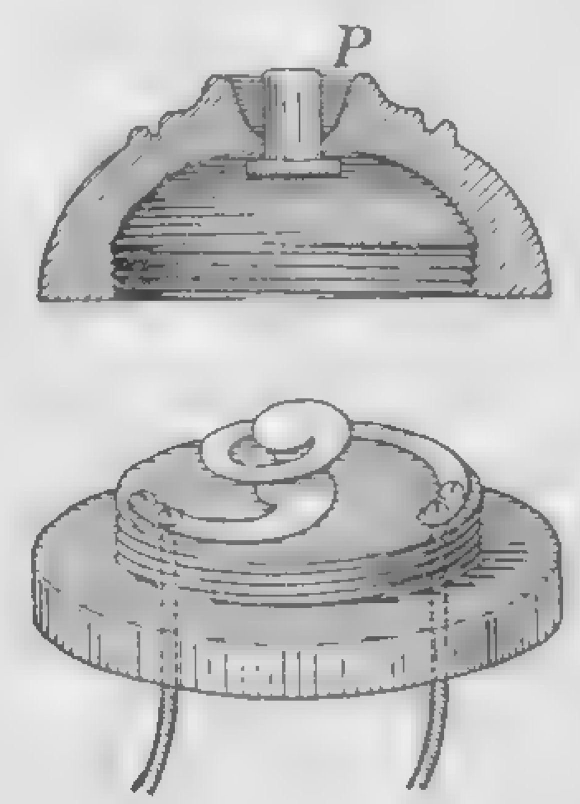


FIG. 271. Cross section of an electric push button

the electromagnet *m* as long as the key *K* is kept closed. As soon as the circuit is broken at *K* the armature is pulled up by the spring *d*. By means of a clockwork device the tape *c* is drawn along at a uniform rate beneath the pencil or pen carried by the armature *b*. A very short time of closing of *K* produces a dot upon the tape; a longer time, a dash. As the Morse, or telegraphic,

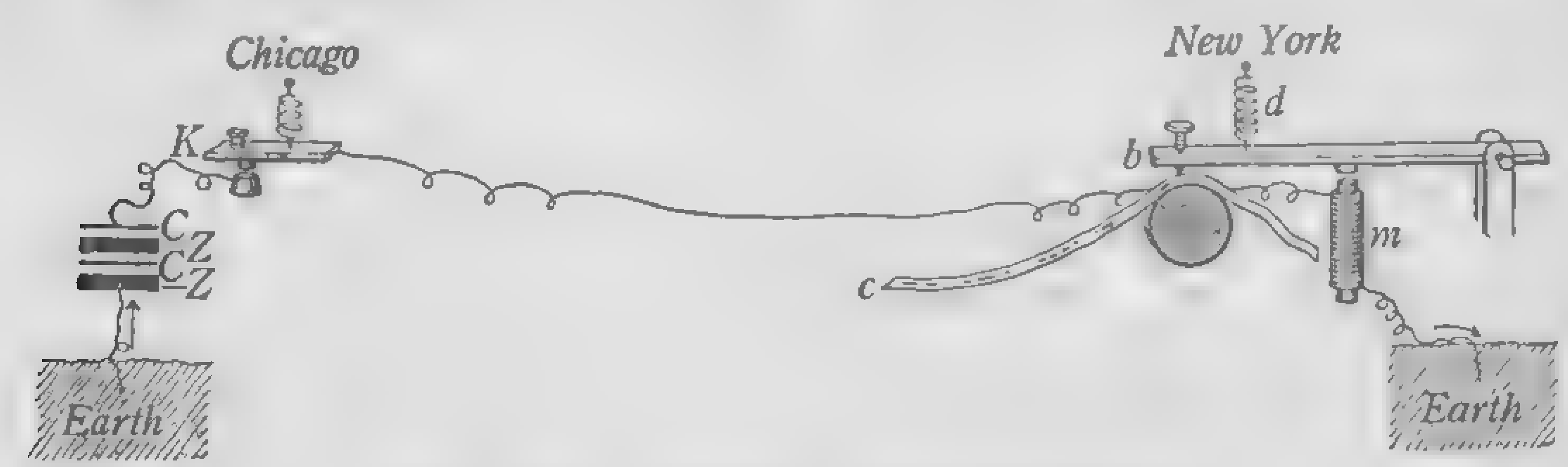


FIG. 272. Principle of the telegraph

alphabet consists of certain combinations of dots and dashes, any desired message may be sent from Chicago and recorded in New York. In modern practice the message is not ordinarily recorded on a tape, for operators have learned to read messages by ear, a very short interval between two clicks being interpreted as a dot, a longer interval as a dash.

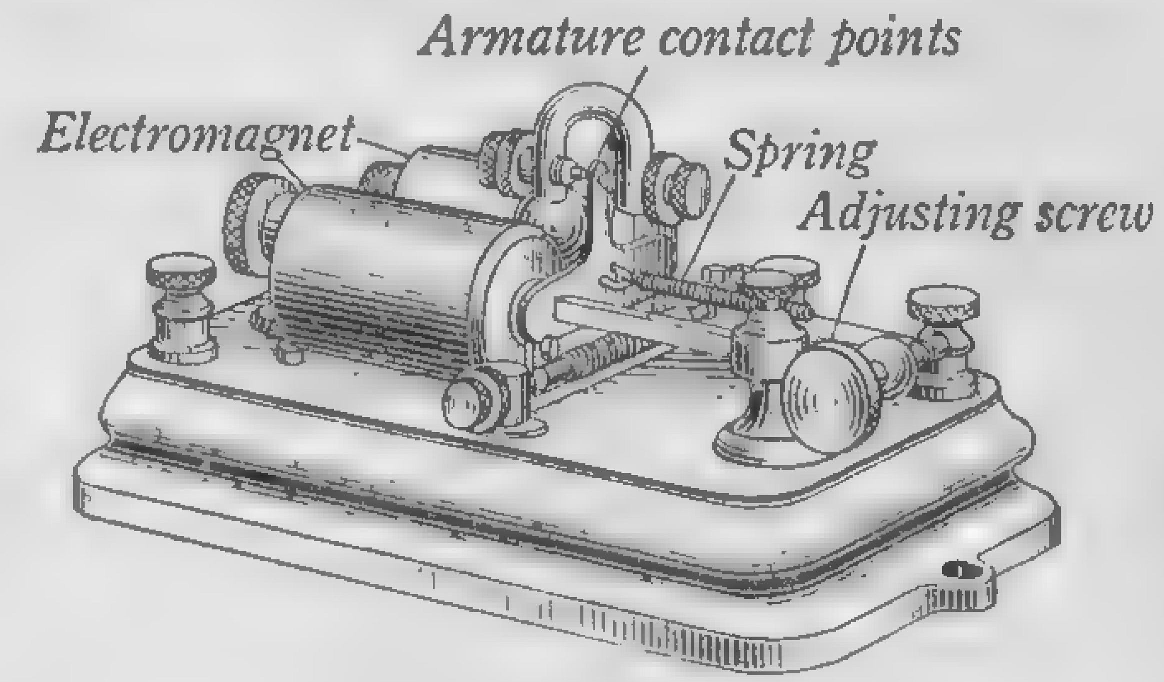


FIG. 273. The relay

The first commercial telegraph line was built by S. F. B. Morse (see opposite page 282) between Baltimore and Washington. It was opened on May 24, 1844, with the now famous message, "What hath God wrought!"

315. The relay and sounder. Since the current that comes over a long telegraph line is of small amperage, the armature of the electromagnet of the receiving instrument must be made very light to respond to the action of the current. The electromagnet of this instrument is made of many thousand turns of fine wire, to secure the requisite number of ampere turns (§ 310) to work the armature. The clicks of such an armature are not sufficiently loud to be read easily by an operator. Hence at each station there is introduced a local circuit, which contains a local battery and a second and heavier electromagnet, which is called a sounder. The electromagnet on the main line is called the relay (Figs. 273 and 275). The sounder has a very heavy armature (Fig. 274, *A*), which is so arranged that it clicks both when

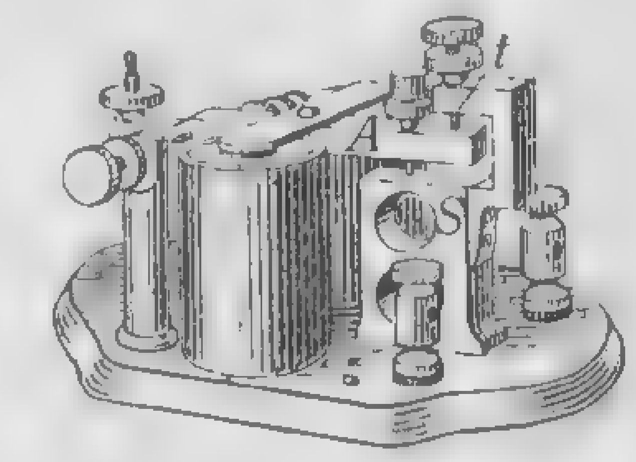


FIG. 274. The sounder

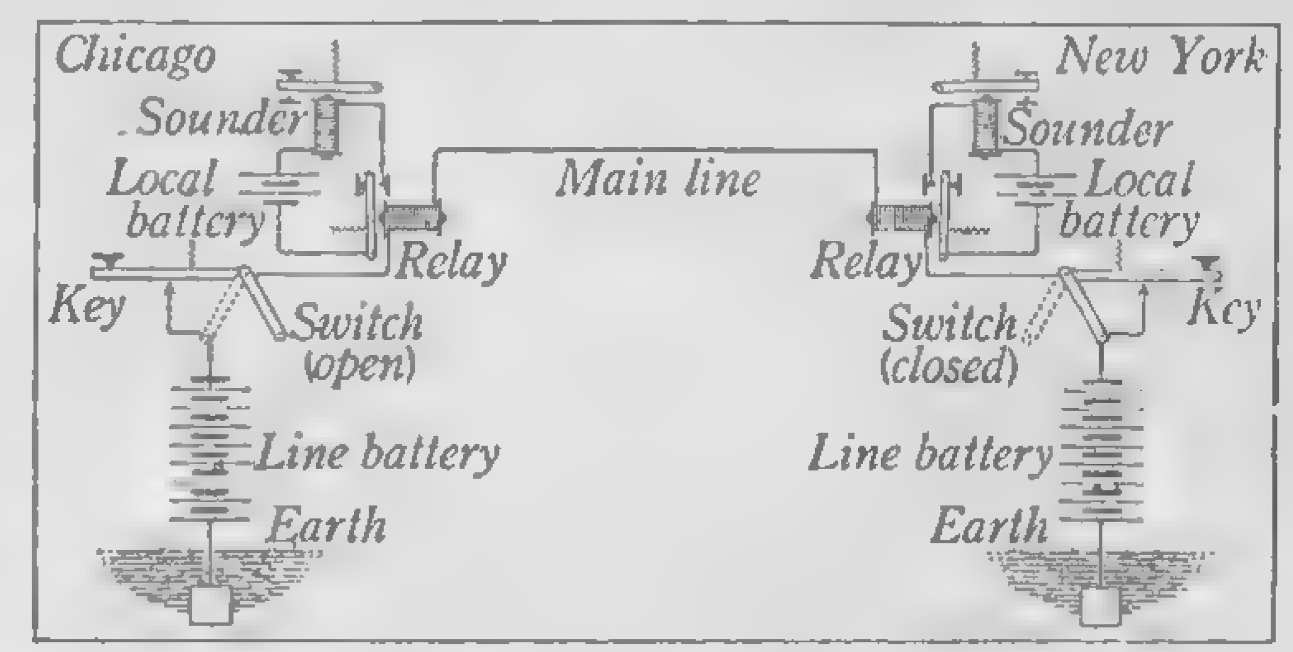


FIG. 275. Simple telegraphic system

it is drawn down by its electromagnet against the stop S and when it is pushed up again by its spring, on breaking the current, against the stop t. The interval which elapses between these two clicks indicates to the operator whether a dot or a dash is sent. The small current in the main line simply serves to close and open the circuit in the local battery which operates the sounder (Fig. 275). The electromagnets of the relay and the sounder differ in that the latter consists of a few hundred turns of coarse wire and carries a comparatively large current.

316. Plan of a telegraphic system. The actual arrangement of the various parts of a telegraphic system is shown in Fig. 275. When an operator at Chicago wishes to send a message to New York, he first opens the switch which is connected to his key, and which is always kept closed except when he is sending a message. He then begins to operate his key, thus controlling the clicks of both his own sounder and that at New York. When the Chicago switch is closed and the one at New York open, the New York operator is able to send a message back over the same line. In practice a message is not usually sent as far as from Chicago to New York over a single line, except in the case of transoceanic cables. Instead it is automatically transferred, say at Cleveland, to a second line, which carries it on to Buffalo, where it is again transferred to a third line, which carries it on to New York. The transfer is made in precisely the same way as the transfer from the main circuit to the sounder circuit. If, for example, the sounder circuit at Cleveland is lengthened so as to extend to Buffalo, and if the sounder itself is replaced by a relay (called in this case a repeater), and the local battery by a line battery, then the sounder circuit has been transformed into a repeater circuit, and all the conditions are met for an automatic transfer of the message at Cleveland.

Summary. The multiple-stroke electric bell depends for its continued action upon an automatic circuit breaker.

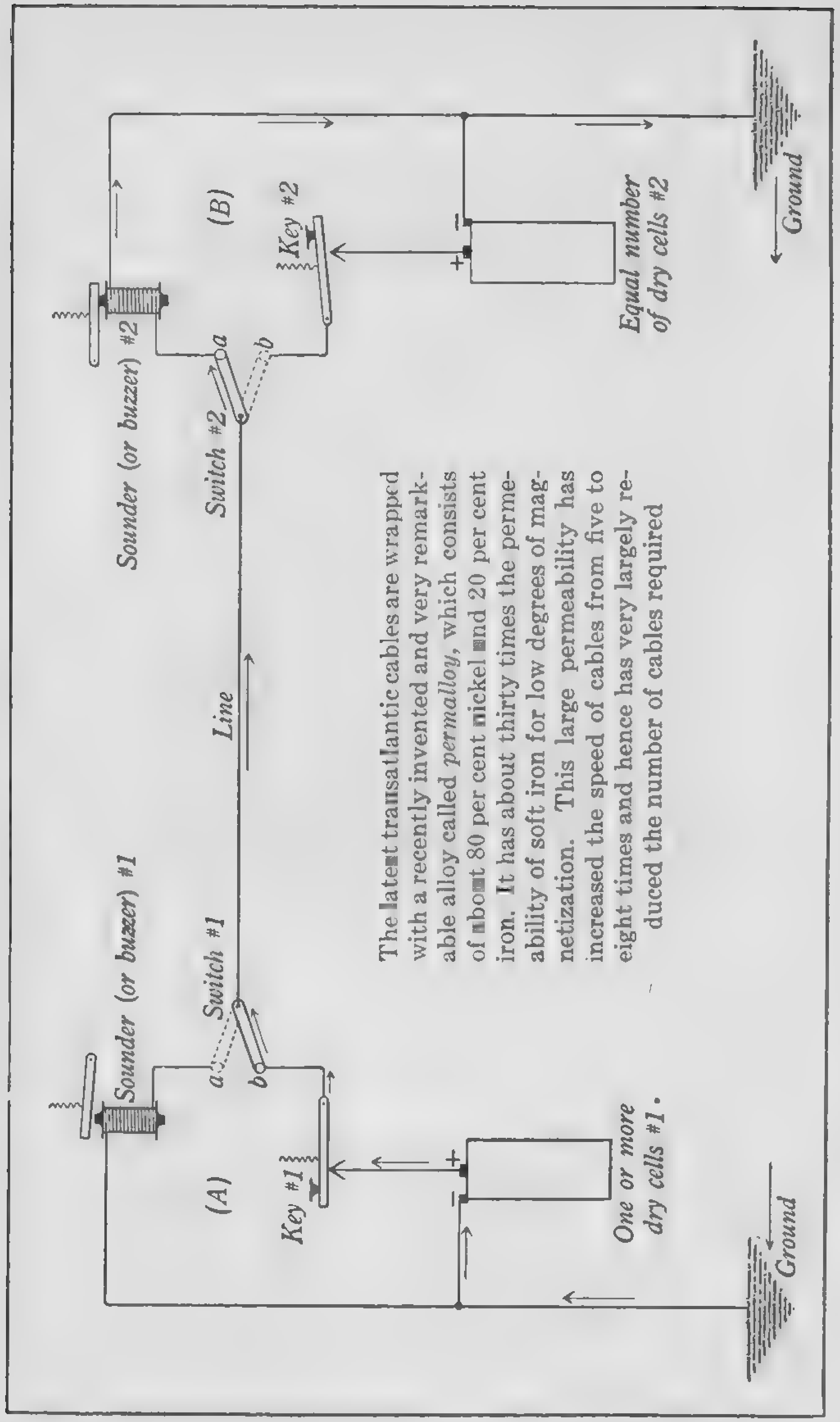
The Morse telegraph system is of the closed-circuit type, the current flowing constantly when the line is not in use.

A telegraph relay receives a very weak current through its helix, which consists of thousands of turns of wire.

A telegraph sounder has only a few turns in its helix, which must carry a relatively strong current to get the necessary ampere turns for operation.

SAMUEL F. B. MORSE (1791–1872)

The inventor of the electromagnetic recording telegraph and of the dot-and-dash alphabet known by his name was born at Charlestown, Massachusetts, graduated at Yale College in 1810, invented the commercial telegraph in 1832, and struggled for twelve years in great poverty to perfect it and secure its proper presentation to the public. The first public exhibition of the completed instrument was made in 1837 at New York University, signals being sent through 1700 feet of copper wire. It was with the aid of a $30,000 grant from Congress that the first commercial line was constructed in 1844 between Washington and Baltimore



A PRACTICAL CIRCUIT FOR A TELEGRAPH LINE BETWEEN HOMES

QUESTIONS AND PROBLEMS

1. Draw a diagram showing how an electric bell works.

2. Draw a diagram of a short two-station telegraph line which has only one instrument at each station.

3. Draw a diagram showing how the relay and sounder operate in a telegraphic circuit. Why is a relay used?

4. A certain relay has 8600 turns of wire in its helix and will operate on .02 ampere. How many ampere turns does this make?

5. In the telegraph system shown in Fig. 275 does a current flow or not when the line is not in use? Why is this necessary?

6. Examine the diagram opposite page 283 and answer the following questions: (1) With switches as shown who does the telegraphing, A or B? (2) How must the switches be set for B to do the sending? Trace the current when B sends. (3) When through sending, how must both switches be left so that either boy may call up the other? (4) Why do the cells not run down even though both switches are at *b* and both keys closed?

Resistance and Electromotive Force

317. Electrical resistance.* Let the circuit of a galvanic cell be connected through a lecture-table ammeter or any low-resistance galvanometer and, for example, 20 ft. of No. 30 copper wire, and let the deflection of the needle be noted. Then let the copper wire be replaced by an equal length of No. 30 German-silver wire. The deflection will be found to be a very small fraction of what it was at first.

A cell, therefore, which is capable of developing a certain fixed electrical pressure is able to force very much more current through a given wire of copper than through an exactly similar wire of German silver. We say, therefore, that German silver offers a higher *resistance* to the passage of electricity than does copper. Similarly, every particular substance has its own characteristic power of transmitting

* This subject should be accompanied and followed by laboratory experiments on Ohm's law, on the comparison of wire resistances, and on the measurement of internal resistances. See, for example, Experiments 40, 41, 42, 45, and 46 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

electrical currents. Since silver is the best conductor known, resistances of different substances are commonly referred to it as a standard, and the ratio between the resistance of a given wire of any substance and the resistance of an exactly similar silver wire is called the *specific resistance* of that substance. The specific resistances of some of the commoner metals in terms of silver are given below:

Silver	1.00	Soft iron	6.00	German silver	18.1
Copper	1.11	Platinum	7.20	Mercury	63.1
Aluminum	1.87	Hard steel	13.5	Nichrome	66.6

The resistance of any conductor is directly proportional to its length and inversely proportional to the area of its cross section or to the square of its diameter.

The unit of resistance is the *ohm,* named after Georg Ohm (see opposite page 290). A length of 9.35 feet of No. 30 copper wire, or 6.2 inches of No. 30 German-silver wire, has a resistance of about one ohm. *The legal definition of the ohm is a resistance equal to that of a column of mercury 106.3 centimeters long and 1 square millimeter in cross section, at 0° C.*

The resistance type of theater dimmer (see opposite page 309) illustrates one of the more important means of controlling and altering the strength of electric currents, namely, the introduction into the circuit of a variable resistance.

318. Resistance and temperature. Let the circuit of a galvanic cell be closed through a galvanometer of very low resistance, and about 10 ft. of No. 30 iron wire wrapped about a strip of asbestos. Let the deflection of the galvanometer be observed as the wire is heated in a Bunsen flame. As the temperature rises higher and higher the current will be found to fall continually.

The experiment shows that *the resistance of iron increases with rising temperature.* This is a general law which holds for all metals. In the case of liquid conductors, on the other hand, the resistance usually decreases with increasing temperature. Carbon and a few other solids show a similar behavior; the filament in the early form of incandescent

electric lamp has when burning at full candle power only about half the resistance that it has when cold.

319. Electromotive force and its measurement.* The potential difference which a galvanic cell or any other generator of electricity is able to maintain between its terminals when these terminals are not connected by a wire — that is, the total electrical pressure which the generator is capable of exerting — is commonly called its *electromotive force,* usually abbreviated to E.M.F. *The E.M.F. of an electrical generator may be defined as its capacity for producing electrical pressure, or P.D.* This P.D. might be measured, as in § 294, by the deflection produced in an electroscope when one terminal is connected to the case of the electroscope and the other terminal to the knob. Potential differences are, in fact, measured in this way in all so-called electrostatic voltmeters.

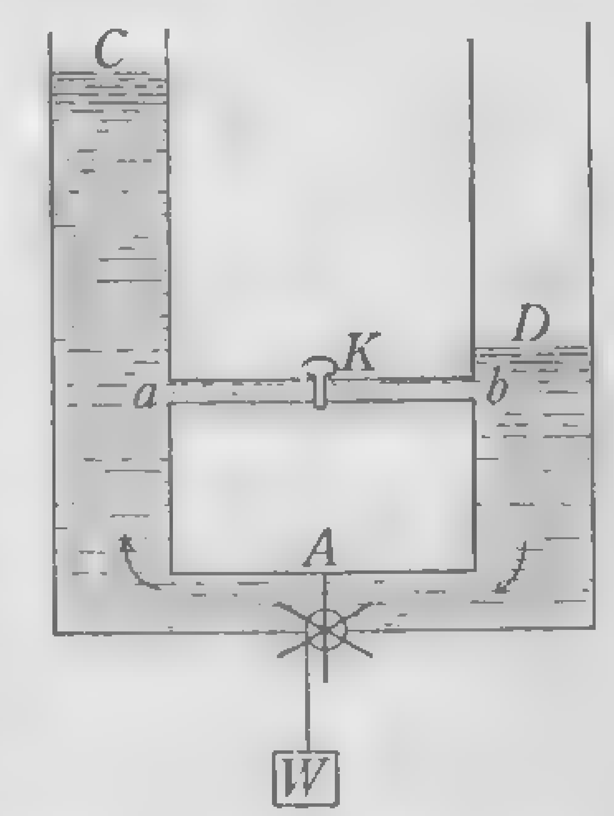


FIG. 276. Hydrostatic analogy of the action of a galvanic cell

The more common type of potential-difference measurer consists, however, of an instrument made like a galvanometer (Fig. 268), except that the coil of wire is made of very many turns of extremely fine wire, so that it carries a very small current. The amount of current which it does carry, however, is proportional to the difference in electrical pressure existing between its ends when these are touched to the two points whose P.D. is sought. The principle underlying this type of voltmeter will be better understood from a consideration of the following water analogy. If the stopcock K (Fig. 276) in the pipe connecting the water tanks C and D is closed, and if the water wheel A is set in motion by applying a weight W, the wheel will turn until it creates such a dif-

* This subject should be preceded or accompanied by laboratory work on E.M.F. See, for example, Experiment 39 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

ference in the water levels between C and D that the back pressure against the left face of the wheel stops it and brings the weight W to rest. In precisely the same way the chemical action within the galvanic cell whose terminals are not joined (Fig. 277) develops positive and negative charges upon these terminals; that is, creates a P.D. between them until the back electrical pressure through the cell due to this P.D. is sufficient to put a stop to further chemical action. The seat of the E.M.F. is at the surfaces of contact of the metals with the acid, where the chemical actions take place.

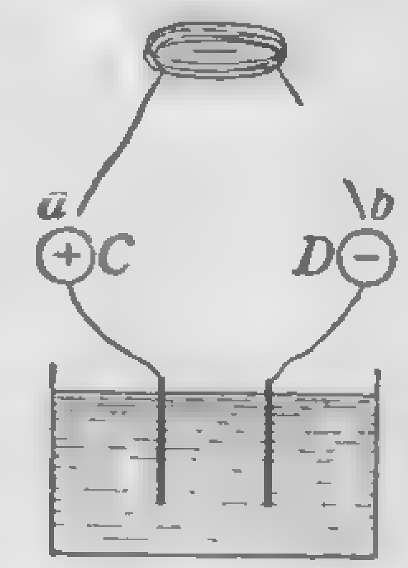


FIG. 277. Measurement of P.D. between the terminals of a galvanic cell

Now, if the water reservoirs (Fig. 276) are put in communication by opening the stopcock K, the difference in level between C and D will begin to fall, and the wheel will begin to build it up again. But if the carrying capacity of the pipe ab is small in comparison with the capacity of the wheel to remove water from D and supply it to C, then the difference of level which permanently exists between C and D when K is open will not be appreciably smaller than when it is closed. In this case the current which flows through ab may obviously be taken as a measure of the difference in pressure which the pump is able to maintain between C and D when K is closed.

In precisely the same way, if the terminals C and D of the cell (Fig. 277) are connected by attaching to them the terminals a and b of any conductor, they at once begin to discharge through this conductor, and their P.D. therefore begins to fall. But if the chemical action in the cell is able to recharge C and D very rapidly in comparison with the ability of the wire to discharge them, then the P.D. between C and D will not be appreciably lowered by the presence of the connecting conductor. In this case the current which flows through the conducting coil, and therefore the deflection of the needle at its center, may be taken as a measure

of the electrical pressure developed by the cell, that is, of the P.D. between its unconnected terminals.

The common voltmeter (Fig. 278) is, then, exactly like an ammeter, except that it offers so high a resistance to the passage of electricity through it that it does not appreciably reduce the P.D. between the points to which it is connected.

320. The commercial voltmeter. In Fig. 279 is shown the principle of construction of the common form of commercial voltmeter. It differs from the ammeter (Fig. 269) in that the shunt is omitted, and a high-resistance coil R is put in series with the moving coil c. The resistance of a voltmeter may be many thousand ohms. The current that passes through it is very small.

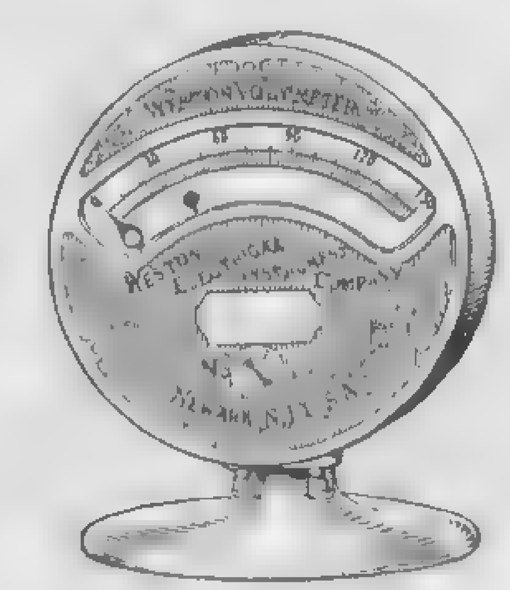


FIG. 278. Lecture-table voltmeter

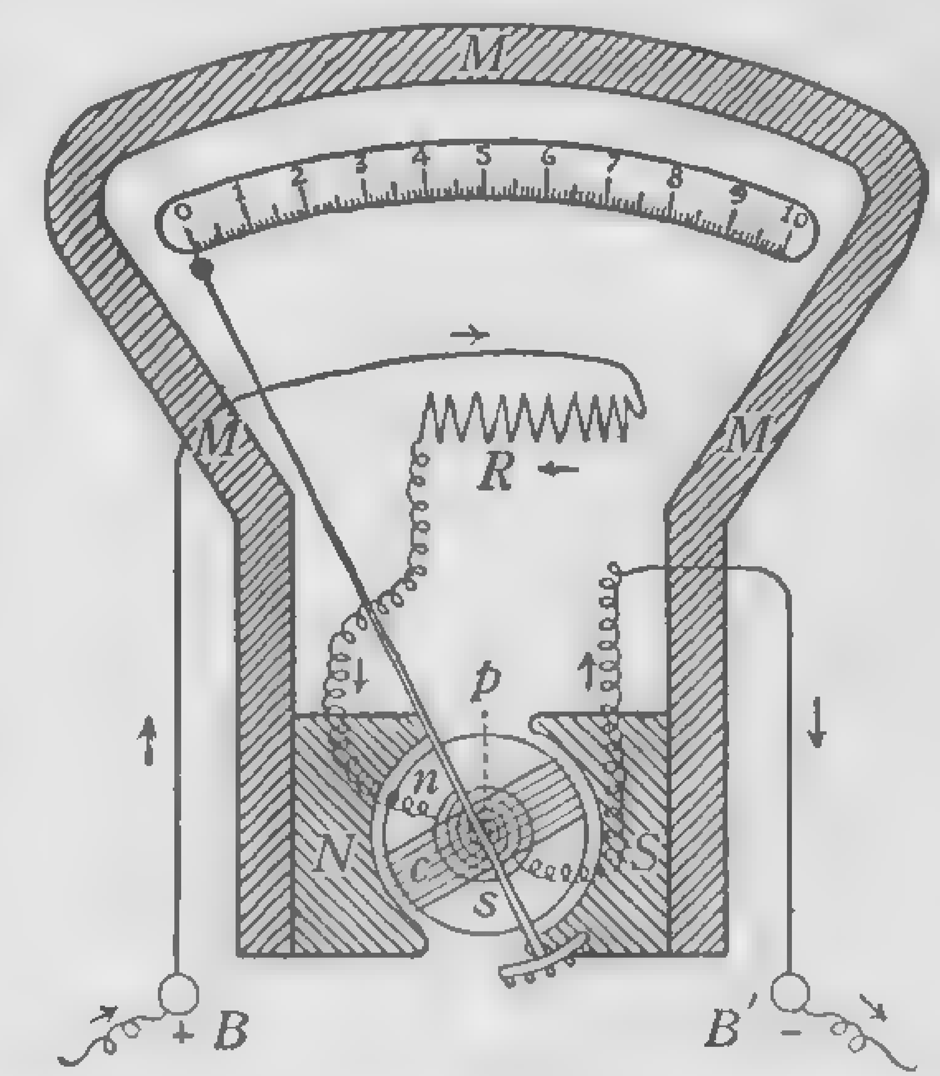


FIG. 279. Principle of commercial voltmeter

321. The electromotive forces of galvanic cells. Let a voltmeter of any sort be connected to the terminals of a simple galvanic cell, like that of Fig. 246. Then let the distance between the plates and the amount of their immersion be changed through wide limits. It will be found that the deflection produced is altogether independent of the shape or size of the plates or their distance apart. But if the nature of the plates is changed, the deflection changes. Thus, copper and zinc in dilute sulphuric acid have an E.M.F. of one volt, carbon and zinc show an E.M.F. of at least 1.5 volts, and carbon and copper show an E.M.F. of

very much less than a volt. Similarly, by changing the nature of the liquid in which the plates are immersed, we can produce changes in the deflection of the voltmeter.*

We learn, therefore, that *the E.M.F. of a galvanic cell depends simply upon the materials of which the cell is composed, and not at all upon the shape, size, or distance apart of the plates.*

322. Fall of potential along a conductor carrying a current. Not only does a P.D. exist between the terminals of a cell on

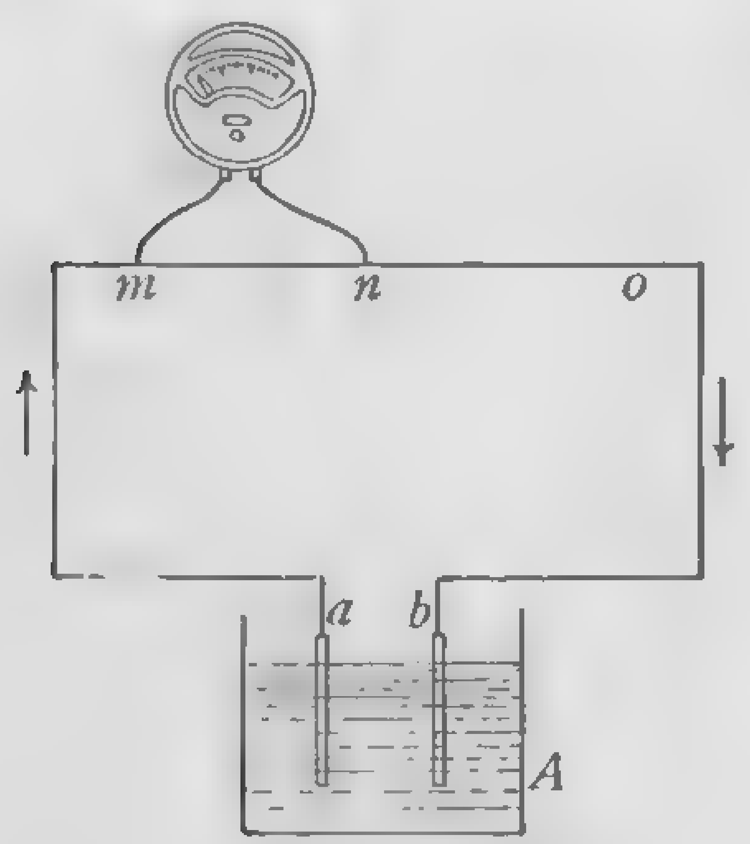


FIG. 280. Showing method of connecting voltmeter to find P.D. between any two points *m* and *n* on an electrical circuit

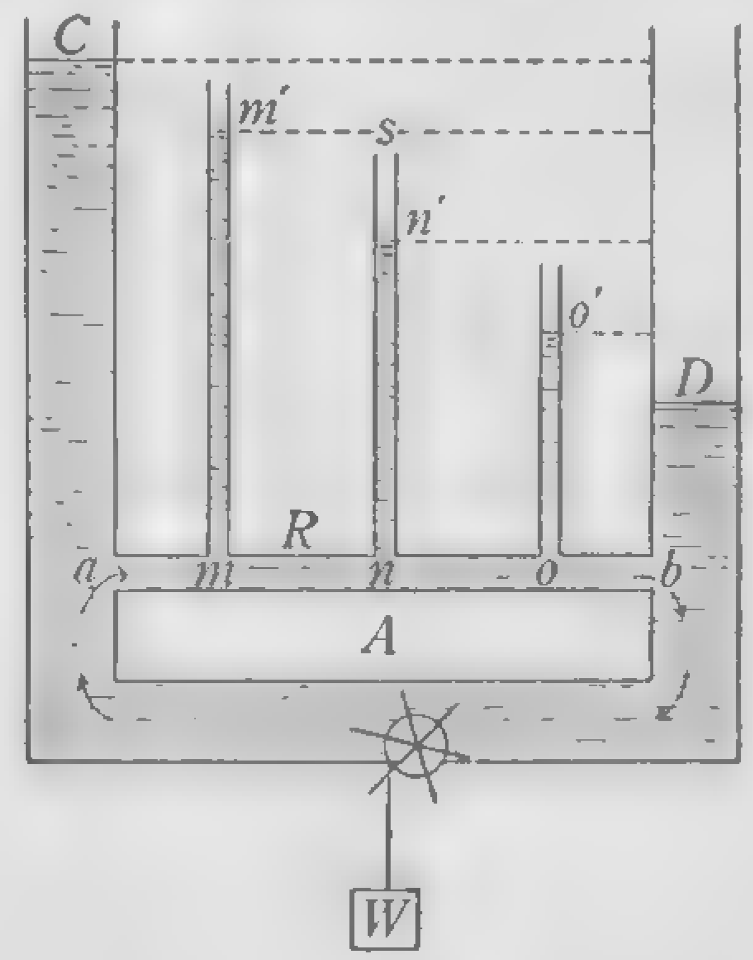


FIG. 281. Hydrostatic analogy of fall of potential in an electrical circuit

open circuit, but also between any two points on a conductor through which a current is passing. For example, in the electrical circuit shown in Fig. 280 the potential at the point *a* is higher than at *m*, that at *m* higher than that at *n*, etc. just as, in the water circuit shown in Fig. 281, the hydrostatic pressure at *a* is greater than that at *m*, that at *m* greater than that at *n*, etc. The fall in the water pressure

* A vertical lecture-table voltmeter (Fig. 278) and a similar ammeter are desirable for this and some of the following experiments, but homemade high-resistance and low-resistance galvanometers, like those described in "Exercises in Laboratory Physics," by Millikan, Gale, and Davis, are thoroughly satisfactory, except for the fact that one student must take the readings for the class.

between *m* and *n* (Fig. 281) is measured by the water head *n's*. If we wish to measure the fall in electrical potential between *m* and *n* (Fig. 280), we touch the terminals of a voltmeter to these points in the manner shown in the figure. Its reading gives us at once the P.D. between *m* and *n* in volts, provided always that its own current-carrying capacity is so small that it does not appreciably lower the P.D. between the points *m* and *n* by being touched across them; that is, provided the current which flows through it is negligible in comparison with that which flows through the conductor which already joins the points *m* and *n*.

SUMMARY. The resistance of a conductor varies directly with its length and inversely with its cross-sectional area or square of its diameter.

$$\frac{r'}{r''} = \frac{l'}{l''}; \quad \frac{r'}{r''} = \frac{s''}{s'} = \frac{d''^2}{d'^2}.$$

The E.M.F. of any generator is the total electrical pressure it can develop on open circuit.

A magnetic voltmeter is a galvanometer calibrated to give a direct reading in volts.

Voltmeters are attached directly in series with a generator to measure its E.M.F., but are used as a shunt to measure fall in potential (P.D.) in any part of a circuit.

X

QUESTIONS AND PROBLEMS

1. If 300 ft. of No. 18 copper wire has a resistance of 2 ohms, what is the resistance of 800 ft. of it?

2. The resistance of a certain piece of German-silver wire is 1 ohm. What will be the resistance of another piece of the same length but of twice the diameter?

3. Consider the diameter of No. 20 wire to be three times that of No. 30. A certain No. 30 wire 1 m. long has a resistance of 6 ohms. What would be the resistance of 4 m. of No. 20 wire made of the same metal?

4. How long a piece of No. 30 copper wire has the same resistance as a meter of No. 30 German-silver wire? (See table of specific resistances, p. 284.)

5. How does the resistance of a tungsten lamp when not lighted compare with its resistance when giving light?

6. If the potential difference between the terminals of a cell on open circuit is to be measured by means of a galvanometer, why must the galvanometer have a high resistance? (See § 319.)

7. In a given circuit the P.D. across the terminals of a resistance of 19 ohms is found to be 3 volts. What is the P.D. across the terminals of a 3-ohm wire in the same circuit?

Ohm's Law

323. Ohm's law. In 1826 Ohm announced the discovery that *the currents furnished by different galvanic cells, or combinations of cells, are always directly proportional to the E.M.F.'s existing in the circuits in which the currents flow, and inversely proportional to the total resistances of these circuits*; that is, if I represents the current in amperes, E the E.M.F. in volts, and R the resistance of the circuit in ohms, then Ohm's law as applied to the complete circuit is

$$I = \frac{E}{R}; \text{ that is, current} = \frac{\text{electromotive force}}{\text{resistance}}. \quad (1)$$

As applied to any portion of an electrical circuit, Ohm's law is

$$I = \frac{\text{P.D.}}{R}; \text{ that is, current} = \frac{\text{potential difference}}{\text{resistance}}, \quad (2)$$

where P.D. represents the difference of potential in volts between any two points in the circuit, and R the resistance in ohms of the conductor connecting these two points. This is one of the most important laws in physics.

Both of the above statements of Ohm's law are included in the equation

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}. \quad (3)$$

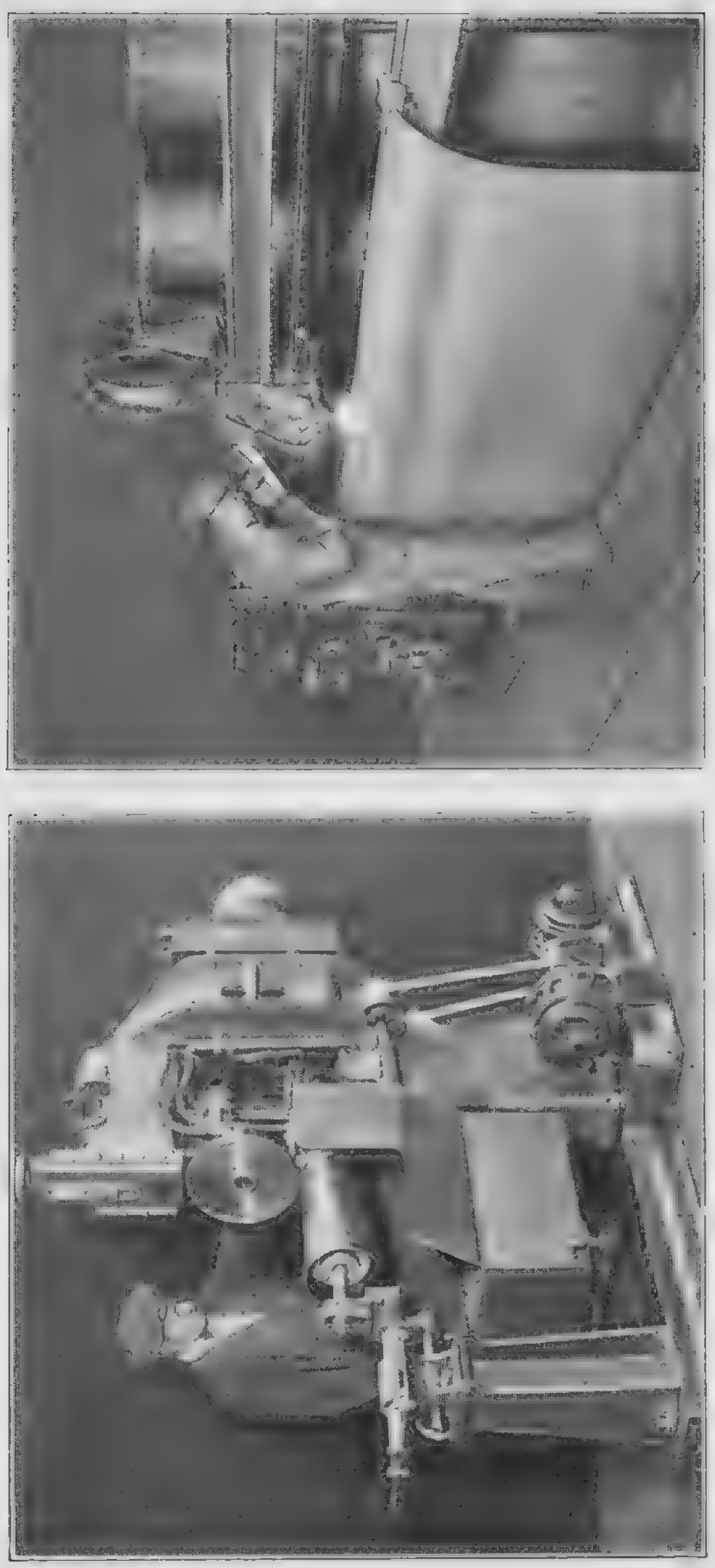
324. Internal resistance of a galvanic cell. Let the zinc and copper plates of a simple galvanic cell be connected to an ammeter, and the distance between the plates then increased. The deflection of the needle will be found to decrease, or if the amount of immersion is decreased, the current also will decrease.

ANDRÉ MARIE AMPÈRE (1775–1836)

A French physicist and mathematician; began his experiments on electromagnetism in 1820, very soon after Oersted's discovery; published his great memoir on the magnetic effects of currents in 1823; first stated the rule for the relation between the direction of a current in a wire and the direction of the magnetic field about it; proposed the theory that terrestrial magnetism is due to currents of electricity flowing around the earth. The ampere, the practical unit of current, is named in his honor

GEORG SIMON OHM (1787–1854)

A German physicist, discoverer of the famous law in physics which bears his name. He was born and educated in Erlangen. It was in 1826, while he was teaching mathematics at a gymnasium in Cologne, that he published his famous paper on the experimental proof of his law. At the time of his death he was professor of experimental physics in the University of Munich. The ohm, the practical unit of resistance, is named in his honor



ELECTRIC WELDERS

At the left is a resistance welding machine. Hundreds of amperes of current pass through the small point of contact of the rotary wheel with the seam to be welded, thus generating the requisite heat. At the right is shown an automatic arc welder in process of welding a seam in a large tank. As much as 100 inches of seam in metals $\frac{1}{4}$ inch thick may be welded in a minute. (Courtesy of the General Electric Company)

Now, since the E.M.F. of a cell was shown in § 321 to be wholly independent of the area of the plates immersed or of the distance between them, it will be seen from Ohm's law that the change in the current in these cases must be due to some change in the total resistance of the circuit. Since the wire which constitutes the outside portion of the circuit has remained the same, we must conclude that *the liquid within the cell, as well as the external wire, offers resistance to the passage of the current.* This internal resistance of the liquid is directly proportional to the distance between the plates, and inversely proportional to the area of the immersed portion of the plates. If, then, we represent the external resistance of the circuit of a galvanic cell by R_e and the internal by R_i, Ohm's law as applied to the entire circuit takes the form

$$I = \frac{E}{R_e + R_i}. \tag{4}$$

Thus, if a simple cell has an internal resistance of 2 ohms and an E.M.F. of 1 volt, the current which will flow through the circuit when its terminals are connected by 9.35 ft. of No. 30 copper wire (1 ohm) is $1./1 + 2 = .33$ ampere.

325. Measurement of internal resistance. A simple method in case both an ammeter and a voltmeter are available is to divide the E.M.F. of the cell as given by the voltmeter by the current which the cell is able to send through the ammeter when connected directly to its terminals; for in this case R_e of equation (4) is negligibly small; therefore $R_i = E/I$. This gives the internal resistance directly in ohms.

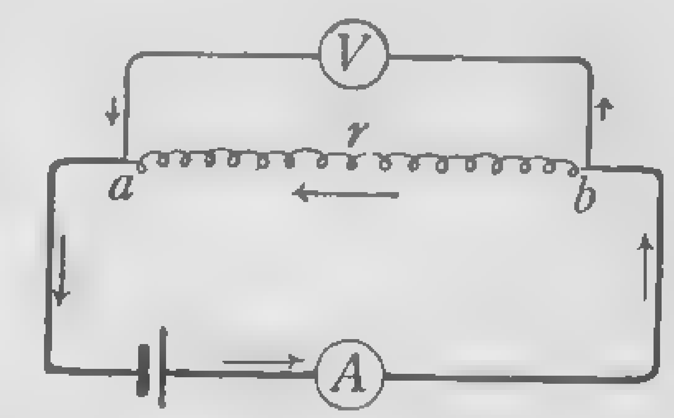


FIG. 282. Measurement of resistance by ammeter-voltmeter method

326. Measurement of any resistance by ammeter-voltmeter method. The simplest way of measuring the resistance of a wire, or, in general, of any conductor, is to connect it into the circuit of a galvanic cell in the manner shown in Fig. 282. The ammeter A is inserted to measure the current, and the voltmeter V to measure the P.D. between the ends a and b of the wire r, the

resistance of which is sought. The resistance of r in ohms is obtained at once from the ammeter and voltmeter readings with the aid of the law $I = \text{P.D.}/R$, from which it follows that $R = \text{P.D.}/I$. Thus, if the voltmeter indicates a P.D. of .4 volt and the ammeter a current of .5 ampere, the resistance of r is $4/5 =$ .8 ohm.*

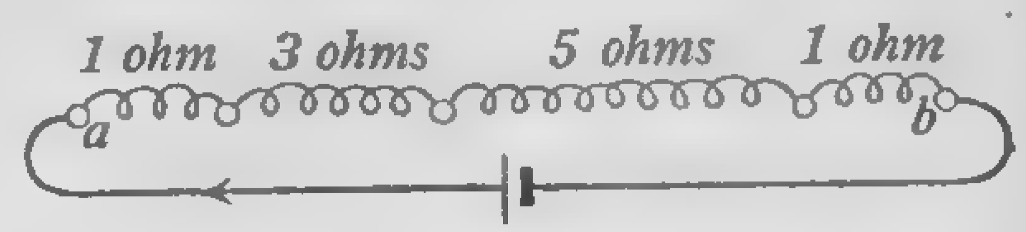


FIG. 283. Series connections

327. Joint resistance of conductors connected in series and in parallel. When resistances are connected as in Fig. 283, so that the same current flows through each of them in succession, they are said to be connected *in series*. The total resistance of a number of conductors so connected is the sum of the several resistances. Thus, in the case shown in the figure the total resistance between a and b is 10 ohms.

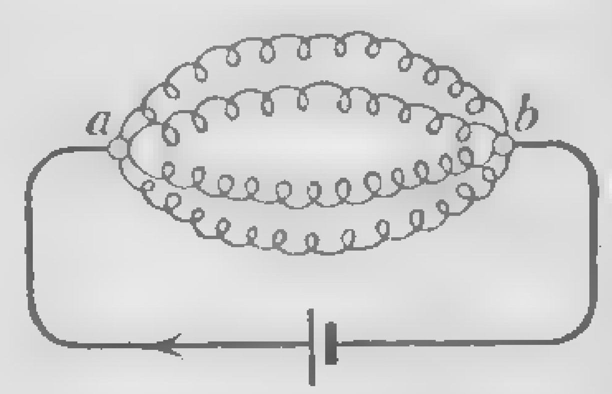


FIG. 284. Parallel connections

When n exactly similar conductors are joined in the manner shown in Fig. 284, that is, *in parallel or multiple*, the actual resistance between a and b is $1/n$ of the resistance of one of them; for obviously, with a given P.D. between the points a and b, four conductors will carry four times as much current as one, and n conductors will carry n times as much current as one. Therefore the resistance, which is inversely proportional to the carrying capacity (see § 323), is $1/n$ as much as that of one.

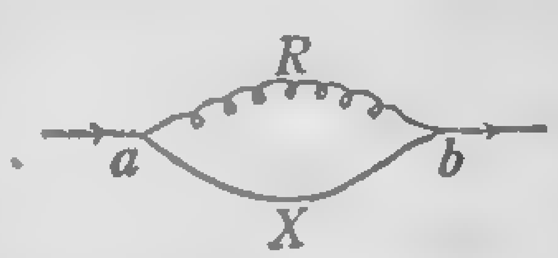


FIG. 285. A shunt

328. Shunts. A wire connected in parallel with another wire is said to be a *shunt* to that wire. Thus, the conductor X (Fig. 285) is said to be shunted across the resistance R. Under such conditions the currents carried by R and X will be inversely proportional to their resistances, so that if X is 1 ohm and R

* For Wheatstone's bridge method see Experiment 42 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

is 10 ohms, R will carry $\frac{1}{10}$ as much current as X, or $\frac{1}{11}$ of the whole current. In other words, since the carrying power, or *conductance*, of X is ten times that of R, ten times as much current will flow through X as through R, or $\frac{10}{11}$ of the whole current will pass through the shunt. The ammeter (Fig. 269) uses a shunt of exceedingly small resistance.

SUMMARY. *Ohm's law.* $\text{Amperes} = \dfrac{\text{volts}}{\text{ohms}}$.

The resistance of any number of conductors in series is the sum of their individual resistances.

The resistance of a group of similar conductors in multiple is equal to the resistance of one of them divided by their number.

In a divided circuit consisting of two branches the strengths of the currents in the branches are inversely proportional to the resistances of the branches.

QUESTIONS AND PROBLEMS

1. How can you prove that the internal resistance of a cell becomes smaller when the plates are made larger? when placed closer together?

2. A certain storage cell having an E.M.F. of 2 volts is found to furnish a current of 20 amperes through an ammeter whose resistance is .05 ohm. Find the internal resistance of the cell.

3. How much current will flow between two points whose P.D. is 2 volts, if they are connected by a wire having a resistance of 12 ohms?

4. If a voltmeter attached across the terminals of an incandescent lamp shows a P.D. of 110 volts and an ammeter connected in series with the lamp indicates a current of .5 ampere, what is the resistance of the incandescent filament? Make a diagram to explain the method.

5. An electric heater has 12 wires of equal resistance connected in parallel. The resistance of each wire when hot is 50 ohms. If the heater is operated on a 110-volt circuit, what will be the total current passing through the heater?

6. Three wires, each having a resistance of 15 ohms, were joined in parallel and a current of 3 amperes sent through them. How much was the P.D. of the ends of the wires?

7. A voltmeter which has a resistance of 2000 ohms is shunted across the terminals A and B of a wire which has a resistance of 1 ohm. What fraction of the total current flowing from A to B will be carried by the voltmeter?

8. From a consideration of the formula $I = E/R$ state in what two ways you may strengthen a current; in what two ways you may weaken it.

Primary Cells

329. Study of the action of a simple cell. If the simple cell already described, that is, zinc and copper strips in dilute sulphuric acid, is carefully observed, it will be seen that, so long as the plates are not connected by a conductor, fine bubbles of gas are slowly formed at the zinc plate, but none at the copper plate. As soon, however, as the two strips are put into metallic connection, bubbles appear in great numbers about the copper plate (Fig. 286), and at the same time a current manifests itself in the connecting wire. These are bubbles of hydrogen. Their appearance on the zinc may be prevented either by using a plate of chemically pure zinc or by amalgamating impure zinc, that is, by coating it over with a thin film of mercury. But the bubbles on the copper cannot be thus disposed of. They are an invariable accompaniment of the current in the circuit. If the current is allowed to run for a considerable time, it will be found that the zinc wastes away, even though it has been amalgamated, but that the copper plate does not undergo any change.

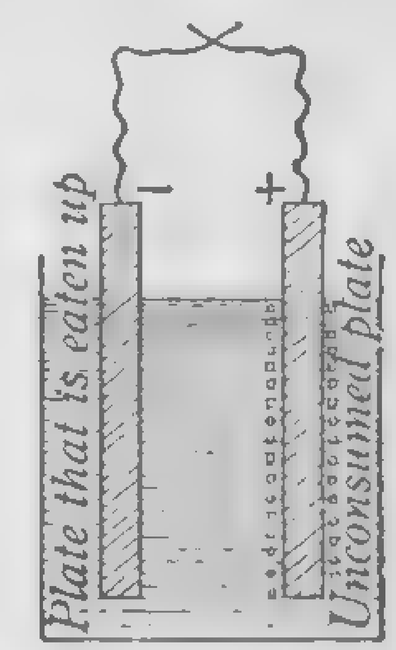


FIG. 286. Chemical actions in the voltaic cell

We learn, therefore, that the electrical current in the simple cell is accompanied by the eating up of the zinc plate by the liquid, and by the evolution of hydrogen bubbles at the copper plate. In every type of galvanic cell, actions similar to these two are always found; that is, *one of the plates is always eaten up, and upon the other plate some element is deposited.* The zinc, which is eaten, is the one which we found to be negatively charged when tested (§ 301); hence when the terminals are connected through a wire, the negative electrons flow through this wire from the zinc plate to the copper plate. This means, in accordance with the convention mentioned in the footnote to § 293, that *the direction of the current through the external circuit is always from the uneaten to the eaten plate.*

330. Local action and amalgamation. The cause of the appearance of the hydrogen bubbles at the surface of impure zinc when dipped in dilute sulphuric acid is that little electrical circuits are set up between the zinc and the small impurities in it (carbon or iron particles) in the manner indicated in Fig. 287. If the zinc is pure, these little local currents cannot be set up, and consequently no hydrogen bubbles appear. Amalgamation stops this so-called *local action*, because the mercury dissolves the zinc, whereas it does not dissolve the carbon, iron, or other impurities. The zinc-mercury amalgam formed is a homogeneous substance which spreads over the whole surface and covers up the impurities. It is important, therefore, to amalgamate the zinc in a battery, in order to prevent the consumption of the zinc when the cell is on open circuit. The zinc is under all circumstances eaten up when the current is flowing, amalgamation serving only to prevent its consumption when the circuit is open.

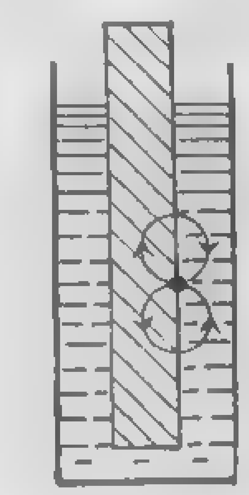


FIG. 287. Local action

331. Theory of the action of a simple cell. A simple cell may be made of any two dissimilar metals immersed in a solution of almost any acid or salt. For simplicity let us examine the action of a cell composed of plates of zinc and copper immersed in a dilute solution of hydrochloric acid. The chemical formula for hydrochloric acid is HCl. This means that each molecule of the acid consists of one atom of hydrogen combined with one atom of chlorine. As was explained under electrolysis (§ 303), the acid, when dissolved in water, dissociates into positively and negatively charged ions (Fig. 288).

When a zinc plate is placed in such a solution, the acid attacks it and pulls zinc atoms into solution. Now, whenever a metal

dissolves in an acid, its atoms, for some unknown reason, go into solution bearing little positive charges. *The corresponding negative charges must be left on the zinc plate* in precisely the same way in which a negative charge is left on silk when positive electrification is produced on a glass rod by rubbing it with the silk. It is in this way, then, that we account for the negative charge which we found upon the zinc plate in the experiment which was performed with the galvanic cell and the electroscope (see § 301).

The passage of positively charged zinc ions into solution gives a positive charge to the solution about the zinc plate; hence the hydrogen ions tend to be repelled away from this plate. When these repelled hydrogen ions reach the copper plate, some of them give up their charges to it and then collect as bubbles of hydrogen gas. It is in this way that we account for the positive charge which we found on the copper plate in the experiment of § 301.

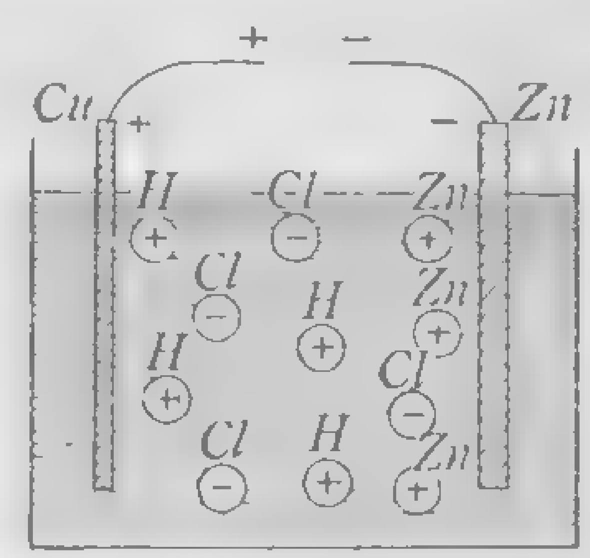


FIG. 288. Showing dissociation of hydrochloric-acid molecules in water

If the zinc and copper plates are not connected by an outside conductor, this passage of positively charged zinc ions into solution continues but a very short time, for the zinc soon becomes so strongly charged negatively that it pulls back on the + zinc ions with as much force as the acid is pulling them into solution. In precisely the same way the copper plate soon ceases to take up any more positive electricity from the hydrogen ions, since it soon acquires a large enough + charge to repel them from itself with a force equal to that with which they are being driven out of solution by the positively charged zinc ions. It is in this way that we account for the fact that on open circuit no chemical action goes on in the simple galvanic cell, the zinc and copper plates simply becoming charged to a definite difference of potential which is called the E.M.F. of the cell.

When, however, the copper and zinc plates are connected by a wire, a current at once flows from the copper to the zinc, and the plates thus begin to lose their charges. This allows the acid to pull more zinc into solution at the zinc plate, and allows more hydrogen to go out of solution at the copper plate. These processes, therefore, go on continuously so long as the plates are connected. Hence a continuous current flows through the connecting

wire until the zinc is all eaten up or the hydrogen ions have all been driven out of the solution, that is, until either the plate or the acid has become exhausted.

332. Polarization. If the simple galvanic cell described is connected to a lecture-table ammeter through two or three feet of No. 30 German-silver wire, the deflection of the needle will decrease slowly; but if the hydrogen is removed from the copper plate (this can be done completely only by removing and thoroughly drying the plate), the deflection will be found to return to its first value.

The experiment shows clearly that the observed falling off in current was due to the collection of hydrogen about the copper plate. This phenomenon of the weakening of the current from a galvanic cell is called the *polarization* of the cell.

333. Causes of polarization. The presence of the hydrogen bubbles on the positive plate causes a diminution in the strength of the current for two reasons: first, since hydrogen is a nonconductor, by collecting on the plate it diminishes the effective area of the plate and therefore increases the internal resistance of the cell; secondly, the collection of the hydrogen about the copper plate lowers the E.M.F. of the cell, because it virtually substitutes a hydrogen plate for the copper plate, and we have already seen (§ 321) that a change in any of the materials of which a cell is composed changes its E.M.F. That there is a real fall in E.M.F. as well as a rise in internal resistance when a cell polarizes may be directly proved in the following way:

Heat a strip of bright, clean sheet copper in the tip of a Bunsen flame until it becomes black with a film of oxide of copper. Let it cool. (If the copper strip is plunged into water to cool it, the film of oxide will be largely detached.) Place it in dilute acid with a zinc plate to make a simple cell. On connecting to a lecture-table galvanometer of medium resistance, the current will remain strong as long as the hydrogen on reaching the copper plate can find oxygen with which to unite. When the supply of oxygen is exhausted, hydrogen bubbles will begin to appear on the copper plate and at the same time the current will weaken rapidly.

The various forms of galvanic cells in common use differ chiefly in the devices employed either for disposing of the hydrogen bubbles or for preventing their formation. The most common types of such cells are described in the following sections.

334. The Daniell cell. The Daniell cell consists of a zinc plate immersed in zinc sulphate and a copper plate immersed in copper sulphate, the two liquids being kept apart either by means of an unglazed earthen cup, or else by gravity.

Copper ions are thus deposited on the negative plate instead of hydrogen and hence the cell is one of very constant electromotive force, 1.08 volts. It is used on continuously closed circuit where constant currents are required.

335. The Weston normal cell; the volt. This cell consists of a positive electrode of mercury in a paste of mercurous sulphate, and a negative electrode of cadmium amalgam in a saturated solution of cadmium sulphate (Fig. 289). It is so easily and exactly reproducible and has an E.M.F. of such extraordinary constancy that it has been taken by international agreement as the standard in terms of which all E.M.F.'s and P.D.'s are rated.

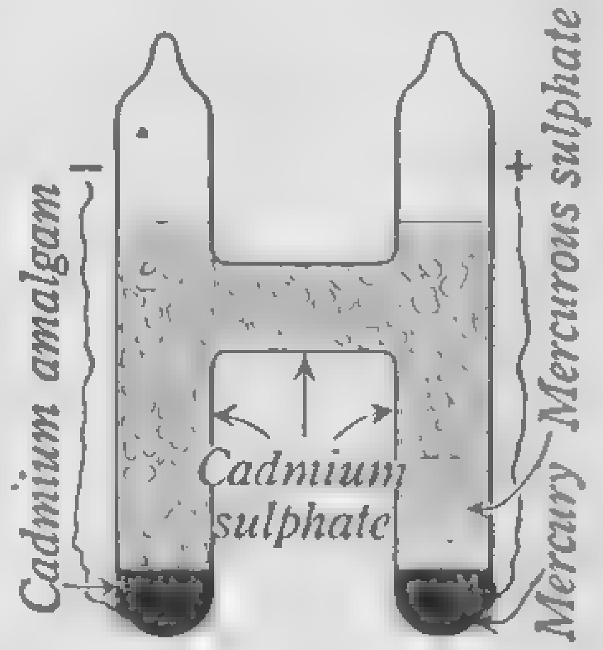


FIG. 289. The Weston normal cell

Thus the *E.M.F. of a Weston normal cell at 20° C. is taken as 1.0183 volts. The legal definition of the volt is then "an electrical pressure equal to $\frac{1}{1.0183}$ of that produced by a Weston normal cell."*

336. The Leclanché cell. The Leclanché cell (Fig. 290) consists of a zinc rod in a solution of ammonium chloride (150 grams to a liter of water) and a carbon plate placed inside a porous cup which is packed full of manganese dioxide and powdered graphite or carbon. As in the simple cell, the zinc dissolves in the liquid, and hydrogen is liberated at the carbon, or positive, plate. Here it is slowly attacked

by the manganese dioxide. This chemical action is, however, not quick enough to prevent rapid polarization when large currents are taken from the cell. The cell slowly recovers when allowed to stand for a while on open circuit. The E.M.F. of a Leclanché cell is about 1.5 volts, and its initial internal resistance is somewhat less than an ohm. It therefore furnishes a momentary current of from one to three amperes.

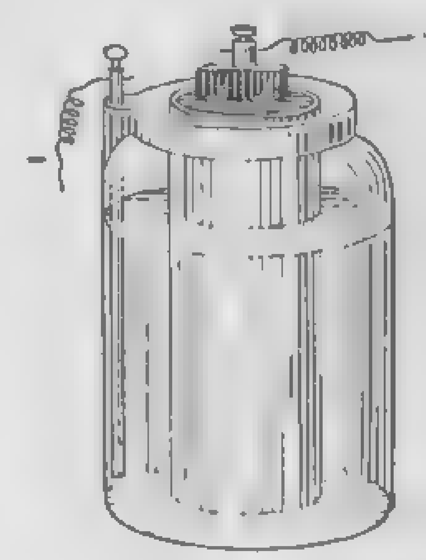


FIG. 290. The Leclanché cell

The immense advantage of this type of cell lies in the fact that the zinc is not at all eaten by the ammonium chloride when the circuit is open, and that therefore, unlike the Daniell cell, it can be left for an indefinite time on open circuit without deterioration. Leclanché cells are used almost exclusively where momentary currents only are needed, as, for example, on doorbell circuits. The cell requires no attention for years at a time, other than the occasional addition of water to replace loss by evaporation, and the occasional addition of ammonium chloride (NH_4Cl) to keep positive NH_4 and negative Cl ions in the solution.

337. The dry cell. The dry cell (Fig. 291) is a modified form of Leclanché cell. It is not really *dry*, since the mixture within is a moist paste. The ordinary dry cell contains approximately 100 grams of water. The zinc plate is in the form of a cylindrical can and holds the moist black mixture in which the carbon plate is embedded. This mixture consists of ammonium chloride, black oxide of manganese, zinc chloride, powdered petroleum coke, and a small amount of graphite. As in the Leclanché cell, it is the action of the

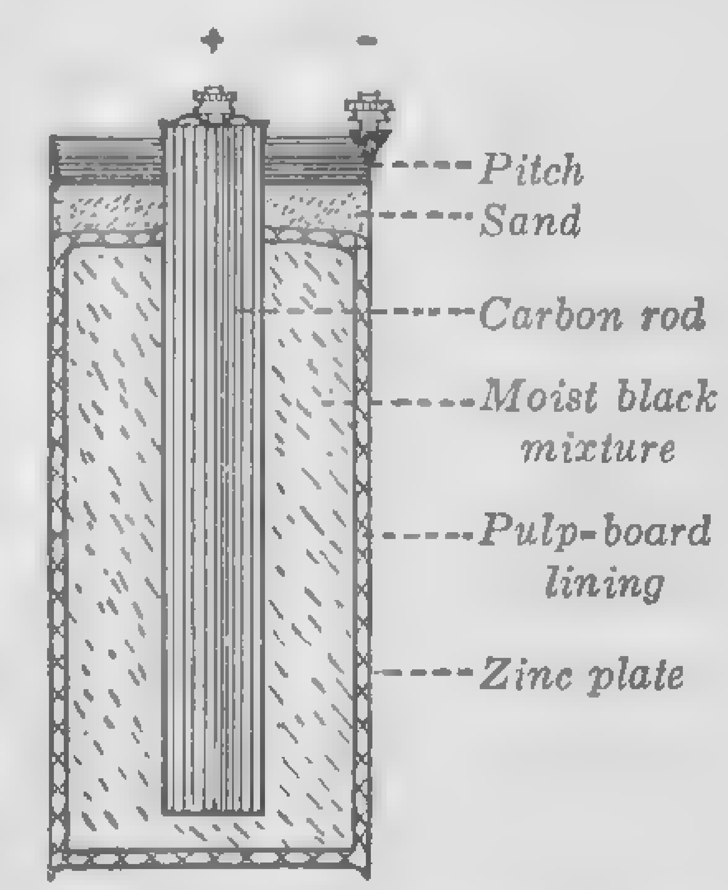


FIG. 291. The dry cell

ammonium chloride upon the zinc which produces the current. The manganese dioxide overcomes the polarization due to hydrogen. The function of the $ZnCl_2$ is to overcome the polarization due to ammonia. The graphite diminishes internal resistance, which, in a fresh cell of ordinary size, may be less than $\frac{1}{20}$ of an ohm. Because of the low internal resistance these cells will deliver 30 or more amperes on momentary short circuit, and on account of their great convenience they are manufactured by the million annually, one firm alone making as high as 30,000 a day.

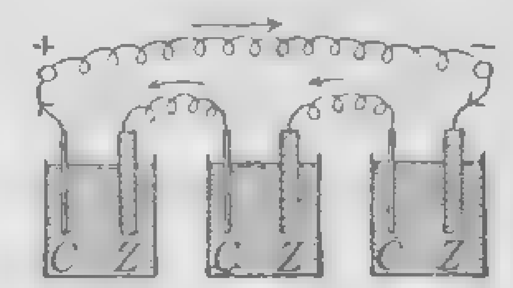


FIG. 292. Cells connected in series

338. Combinations of cells. There are two ways in which cells may be combined: first, *in series*; and, secondly, *in parallel*. When they are connected in series, the zinc of one cell is joined to the copper of the second, the zinc of the second to the copper of the third, etc., the copper of the first and the zinc of the last being joined to the ends of the external resistance (see Fig. 292). The E.M.F. of such a combination is the sum of the E.M.F.'s of the single cells. The internal resistance of the combination is also the sum of the internal resistances of the single cells. Hence, if the external resistances are very small, the current furnished by the combination will be no larger than that furnished by a single cell, since the total resistance of the circuit has been increased in the same ratio as the total E.M.F. But if the external resistance is large, the current produced by the combination will be very much greater than that produced by a single cell. Just how much greater can always be determined by applying Ohm's law;

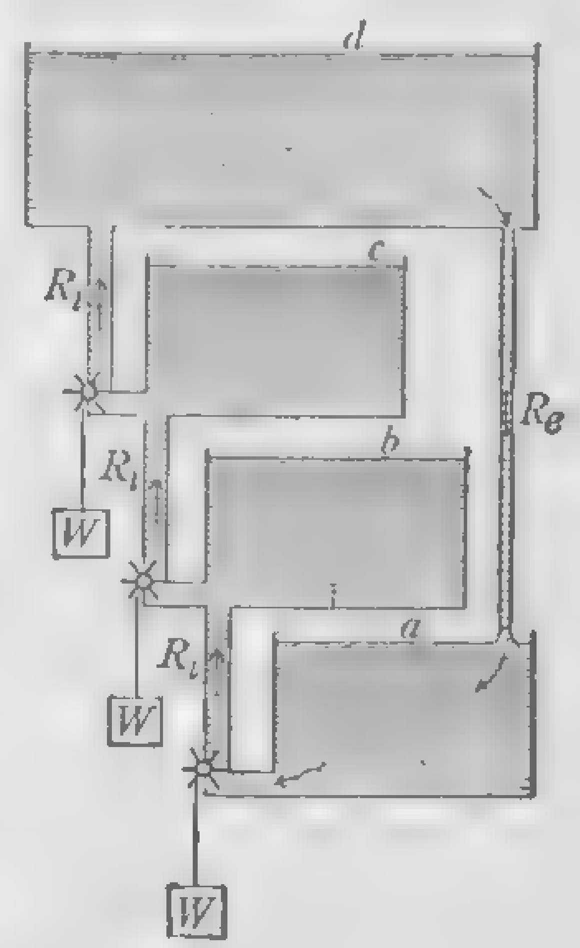
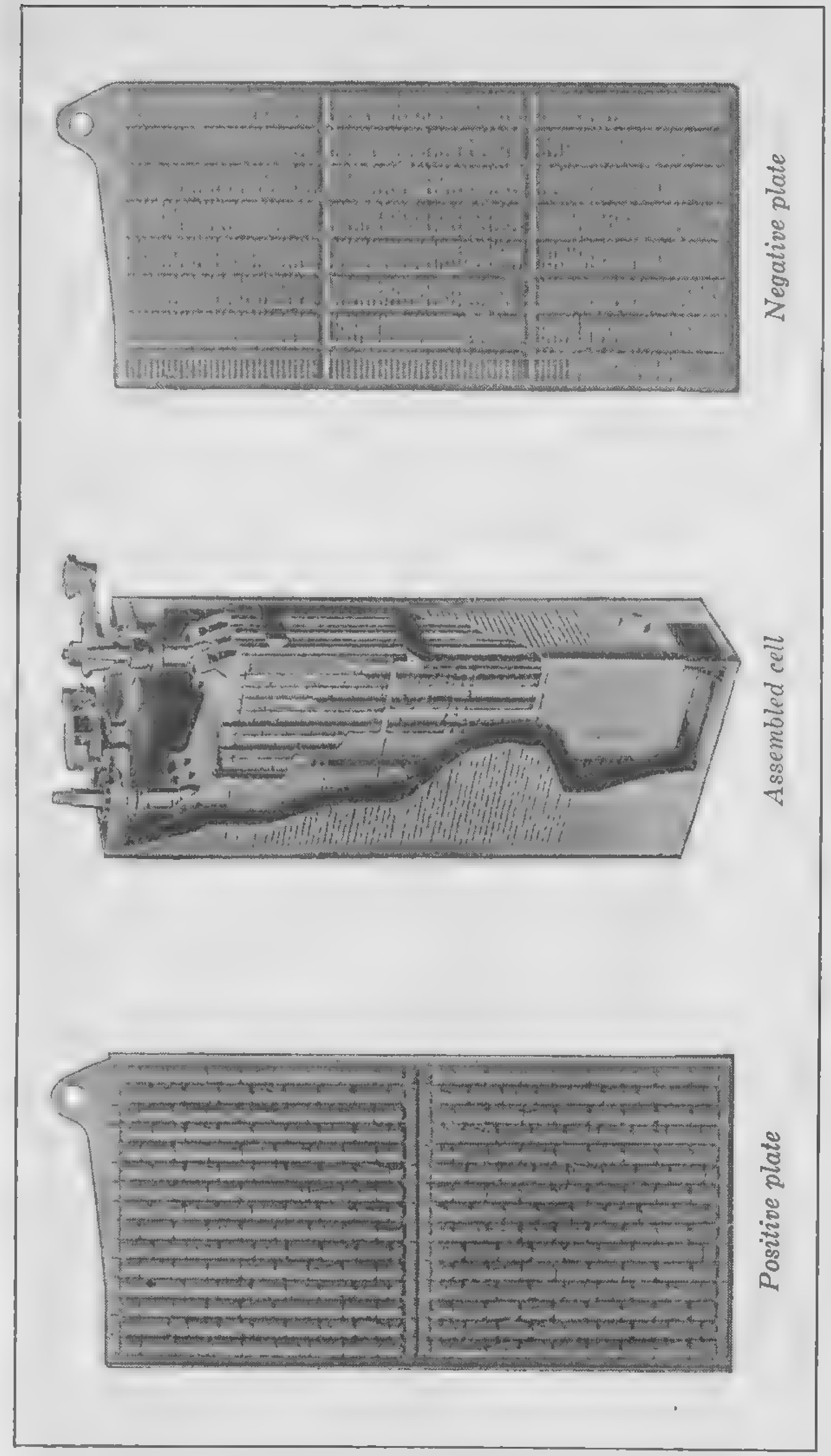
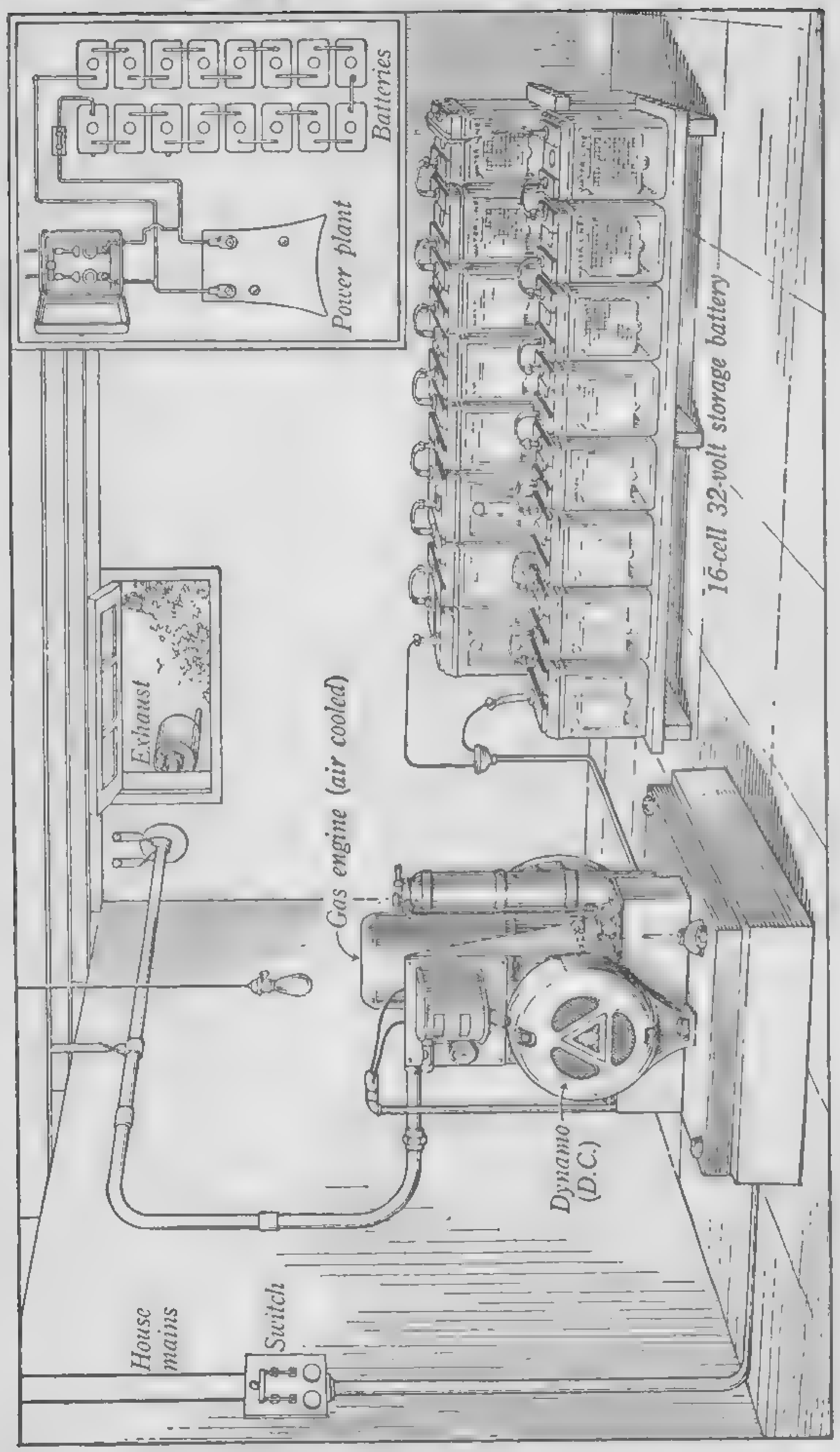


FIG. 293. Water analogy of cells in series



THE EDISON NICKEL-IRON, CAUSTIC-POTASH STORAGE CELL

This cell (see § 340) consists of an electrically welded steel can which contains the potassium-hydroxide electrolyte. The positive plate is a grid holding perforated cylindrical steel capsules containing peroxide of nickel mingled with pure metallic nickel flakes. The negative plate consists of a grid retaining perforated flat steel capsules filled with finely divided iron



A SMALL ELECTRIC-LIGHT AND POWER PLANT FOR RURAL HOMES

This little plant consists of a small gasoline engine, dynamo, and storage battery. The generator charges the battery, which (when the generator is not running) supplies the current for illumination and power. In case light and power are being utilized while the generator is running, the battery "floats" on the line, as indicated by the wiring diagram in the upper right-hand corner. This means that when the load is small, the battery is *receiving* a charge; but when the demand for current is *great*, the battery *delivers* current, thus helping the generator to do the work

for if there are n cells in series, and E is the E.M.F. of each cell, the total E.M.F. of the circuit is nE. Hence, if R_e is the external resistance and R_i the internal resistance of a single cell, then Ohm's law gives

$$I=\frac{nE}{R_e+nR_i}.$$

If the n cells are connected in parallel, that is, if all the coppers are connected together and all the zincs, as in Fig. 294, the E.M.F. of the combination is only the E.M.F. of a single cell, whereas the internal resistance is $1/n$ of that of a single cell, since connecting the cells in this way is simply equivalent to multiplying the area of the plates n times. The current furnished by such a combination will be given by the formula

$$I=\frac{E}{R_e+\frac{R_i}{n}}.$$

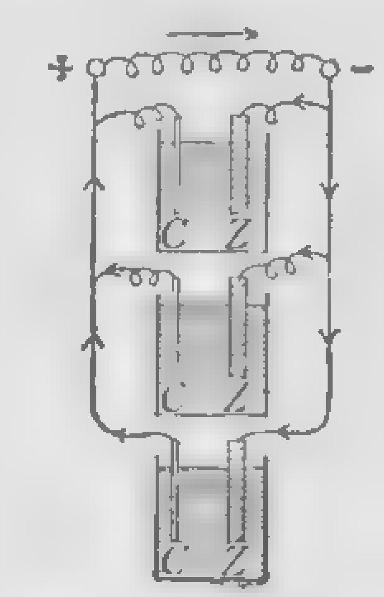


FIG. 294. Cells in parallel

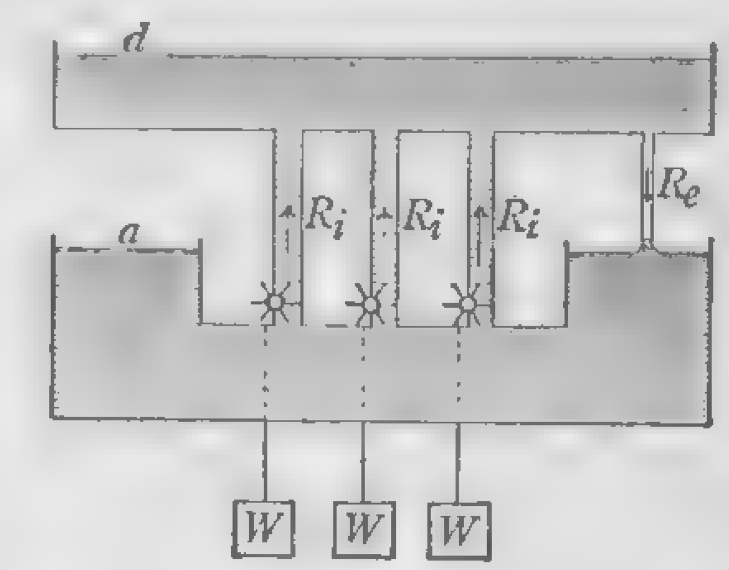


FIG. 295. Water analogy of cells in parallel

If, therefore, R_e is negligibly small, as in the case of a heavy copper wire, the current flowing through it will be n times as great as that which could be made to flow through it by a single cell. Figs. 293 and 295 show by means of the water analogy why the E.M.F. of cells in series is the sum of the several E.M.F.'s, and why the E.M.F. of cells in parallel is no greater than that of a single cell. These considerations show that the rules which should govern the combination of cells are as follows: *Connect in series when R_e is large in comparison with R_i; connect in parallel when R_i is large in comparison with R_e.*

SUMMARY. One of the plates of a galvanic cell is eaten up, whereas some element is deposited on the other.

Polarization in the simple cell is due to an accumulation of hydrogen on the uneaten plate.

Similar cells in series give increased E.M.F., but increased internal resistance also, both in direct proportion to the number of cells.

Similar cells in multiple give no increase in E.M.F., but the internal resistance of such a group is that of one cell divided by the number of cells.

Ohm's law applied to any group of cells. The strength of the current is equal to the effective E.M.F. of the group divided by the sum of the resistances of the external circuit and of the group.

QUESTIONS AND PROBLEMS

1. (1) What are the + and − ions found in a dilute solution of H_2SO_4? (2) When atoms from the Zn plate of a cell are pulled into solution by the acid, what kind of charge do the Zn ions carry? What sort of charge does this leave on the Zn plate? (3) What do these + ions close about the Zn plate do to the + H ions of the electrolyte? (4) When these + H ions reach the other plate, what becomes of their + charges? (5) Why does a current flow through a wire connecting the two plates of a voltaic cell?

2. Why is a Leclanché cell better than a Daniell cell for doorbell circuits?

3. Why would you not consider using dry cells on such a telegraph line as that shown in Fig. 275? Why can you use them on such a line as is shown opposite page 281?

4. A certain dry cell having an E.M.F. of 1.5 volts delivered a current of 30 amperes through an ammeter having a negligible resistance. Find the internal resistance of the cell.

5. Explain the rapid weakening of a dry cell when you connect it directly to an ammeter.

6. Diagram three wires in series and three cells in series. If each wire has a resistance of .1 ohm, what is the resistance of the series? If each cell has a resistance of .1 ohm, what is the internal resistance of the series?

7. Diagram three wires in parallel or multiple, and three cells in multiple. If each wire has a resistance of 6 ohms, what is the joint resistance of the three? If each cell has an internal resistance of 6 ohms, what is the resistance of the group?

8. A cell of internal resistance .05 ohm and electromotive force 1.5 volts is connected with three resistances of 12 ohms each. Calculate the current flowing through the circuit (1) when the three resistances are connected in parallel; (2) when the three resistances are connected in series.

9. What did Faraday discover concerning the influence of time and of strength of current upon the amount of chemical change produced in a cell? (See § 306.)

10. If 10 dry cells in series deliver a total current of 10 amperes and 10 other dry cells in multiple on another circuit deliver 10 amperes to the external circuit, how does the rate at which zinc is being consumed in the first group compare with the rate of consumption in the second?

11. Four new dry cells connected in series delivered a current of 2 amperes to an electromagnet whose helix had a resistance of 2.8 ohms. (1) What was the internal resistance of each dry cell, the electromotive force of each cell being 1.5 volts? (2) If the helix consisted of 100 turns, to how many ampere turns was the magnetic effect due?

12. Ordinary No. 9 telegraph wire has a resistance of 20 ohms to the mile. What current will 100 Daniell cells in series, each of E.M.F. of 1 volt, send through 100 mi. of such wire, if the two relays have a resistance of 150 ohms each and the cells an internal resistance of 4 ohms each?

13. If the relays of the preceding problem had each 10,000 turns of wire in their coils, how many ampere turns were effective in magnetizing their electromagnets?

14. If, on the above telegraph line, sounders having a resistance of 3 ohms each and 500 turns were to be put in the place of the relays, how many ampere turns would be effective in magnetizing their cores? Why, then, does the electromagnet of the relay have a high resistance?

SECONDARY CELLS

339. Lead storage batteries. Let two 6-by-8-inch lead plates be screwed to a half-inch strip of some insulating material, as in Fig. 296, and immersed in a solution consisting of one part of sulphuric acid to ten parts of water. Let a current from two stor-

age or three dry cells in series, C, be sent through this arrangement, an ammeter A or any low-resistance galvanometer being inserted in the circuit. As the current flows, hydrogen bubbles will be seen to rise from the cathode (the plate at which the current leaves the solution), while the positive plate, or anode, will begin to turn dark brown. At the same time the reading of the ammeter will be found to decrease rapidly. The brown coating is a compound of lead and oxygen, called lead peroxide (PbO_2), which is formed by the action upon the plate of the oxygen which is liberated, precisely as in the experiment on the electrolysis of water (§ 303). Now let the batteries be removed from the circuit by opening the key K_1, and let an electric bell B be inserted in their place by closing the key K_2. The bell will ring and the ammeter A will indicate a current flowing in a direction opposite to that of the original current. This current will decrease rapidly as the energy which was stored in the cell by the original current is expended in ringing the bell.

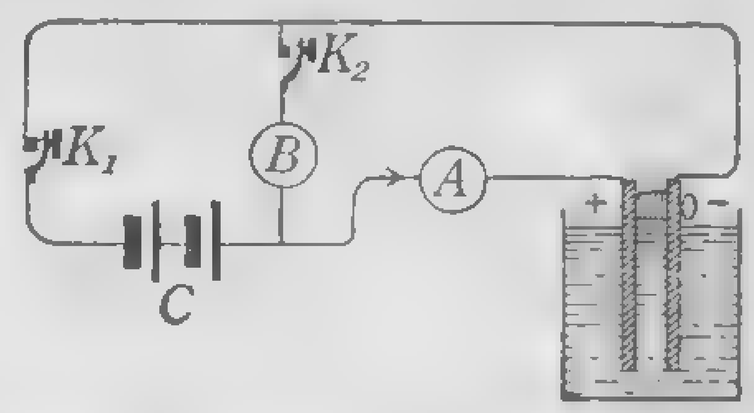


FIG. 296. The principle of the storage battery

This experiment illustrates the principle of the *storage battery.* Properly speaking, there has been no storage of *electricity,* but only a storage of *chemical energy.*

Two similar lead plates have been changed by the action of the current into two dissimilar plates, one of lead and one of lead peroxide; in other words, an ordinary galvanic cell has been formed, for any two dissimilar metals in an electrolyte constitute a primary galvanic cell. In this case the lead peroxide plate corresponds to the copper of an ordinary cell, and the lead plate to the zinc. This cell tends to create a current opposite in direction to that of the charging current; that is, its E.M.F. pushes back against the E.M.F. of the charging cells. It was for this reason that the ammeter reading fell. When the charging current is removed, this cell acts exactly like a *primary* galvanic cell and furnishes a current until the thin coating of peroxide is used up. The only important difference between a commercial storage cell (Fig. 297) and the

one which we have here used is that the former is provided in the making with a much thicker coat of the "active material" (lead peroxide on the positive plate and a porous, spongy lead on the negative) than can be formed by a single charging such as we used. This material is pressed into interstices in the plates, as shown in Fig. 297. The E.M.F. of the lead storage cell is about 2 volts. Since the plates are always very close together and may be given any desired size, the internal resistance is usually small, so that the currents furnished may be of very large amperage.

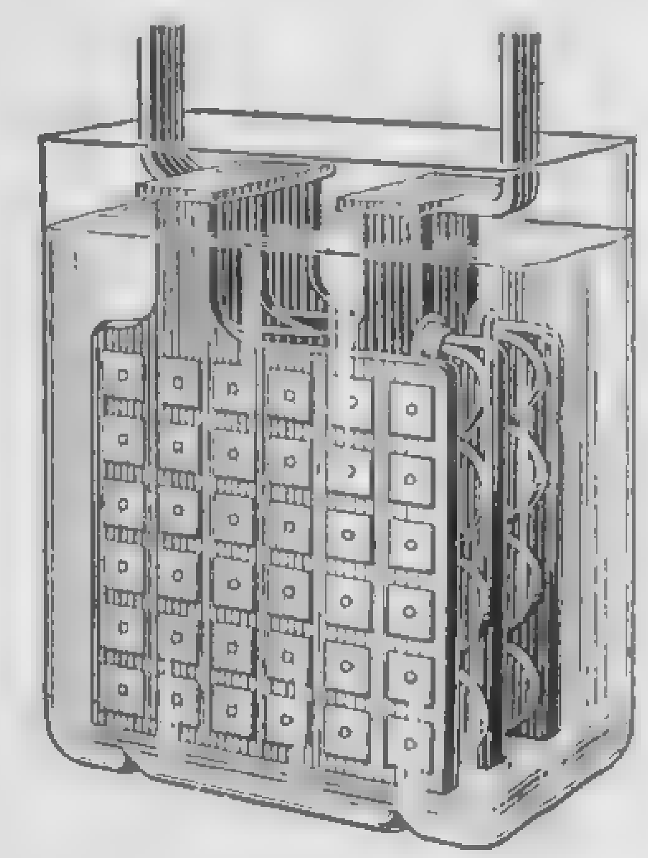


FIG. 297. Lead-plate storage cell

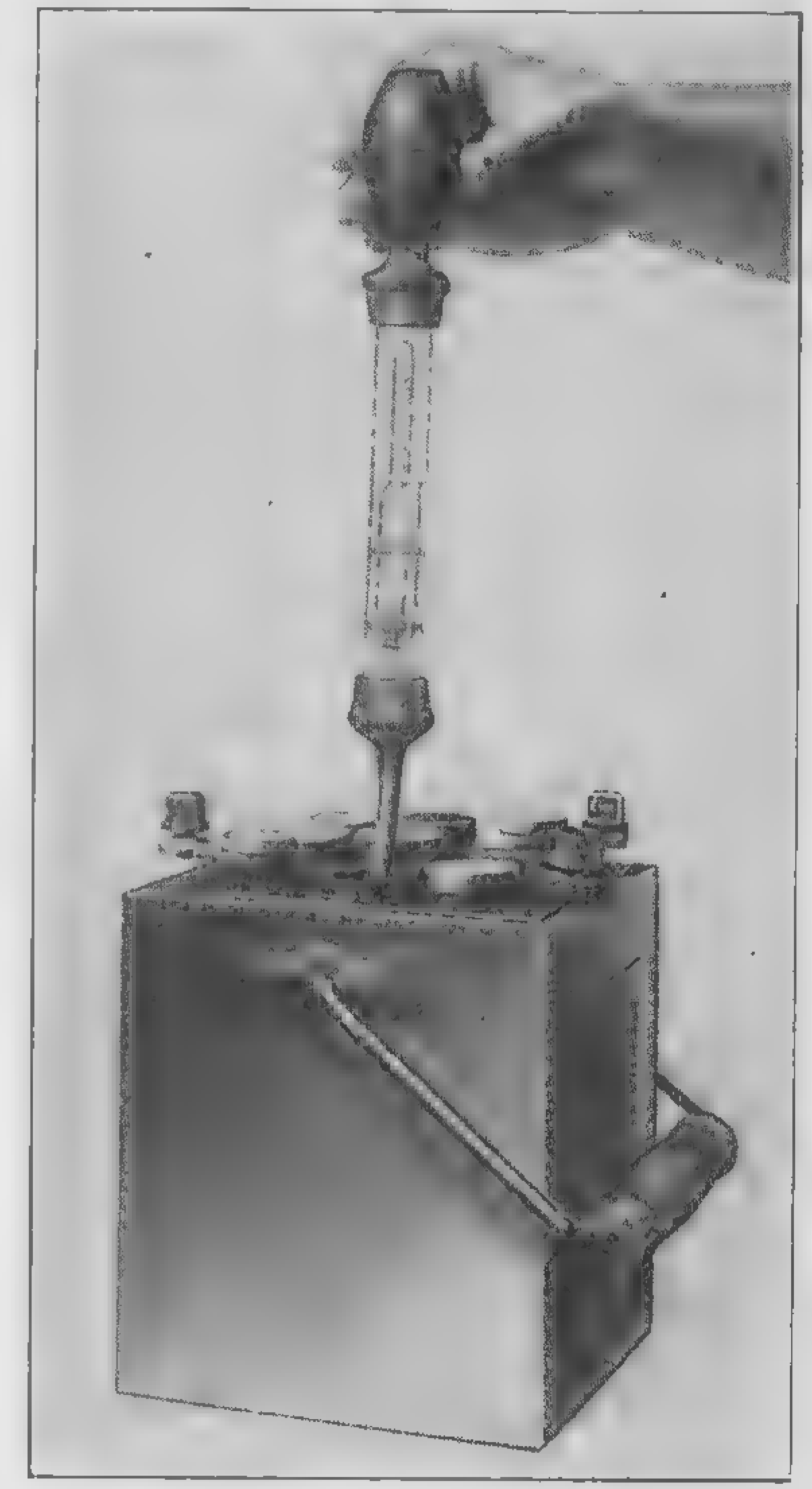


FIG. 298. Taking the specific gravity of the electrolyte

The usual efficiency of the lead storage cell is about 75 per cent; that is, only about three fourths as much electrical energy can be obtained from it as is put into it.

The amount of *charge* to be used in a lead storage cell is determined by taking the specific gravity of its electrolyte (Fig. 298).

340. Nickel-iron storage batteries. Thomas A. Edison (see opposite page 382) developed and perfected the nickel-iron caustic-potash storage cell. The electrolyte is a 21 per cent solution of caustic potash in water to which is added a small amount of lithium hydroxide. The negative plates contain iron powder securely retained in perforated, flat, rectangular capsules, and the positive plates contain nickel peroxide in perforated cylindrical containers. For equal capacities the Edison cell weighs about half as much as the lead cell, and it will stand a remarkable amount of electrical and mechanical abuse. The E.M.F. is about 1.2 volts. Because of large internal resistance these cells are not adapted to starting automobiles; their especial field is as a source of motive power for electric trucks and battery-driven street cars. In efficiency the Edison cell (see opposite page 300) is a little below the lead cell.

Summary. The energy of an electric current does work upon a storage battery in charging it, thus storing potential energy in chemical form.

When a storage battery discharges, the stored chemical energy changes back to electrical energy.

QUESTIONS AND PROBLEMS

1. The lead peroxide plate and the nickel peroxide plate are both called the *positives*. What is the relation of the charging current to these plates?

2. In charging a storage battery is it better to say that the current passes *into* the cell or *through* it? What is *stored*?

3. If an automobile is equipped with 6-volt lamps, how many lead storage cells must be on the car? Are these cells in series or multiple?

4. If you attempted to charge a storage battery with a current having the same voltage as the battery, what would be the result? Explain.

Heating Effects of the Electric Current

341. Heat developed in a wire by an electric current. Let the terminals of two or three dry cells in series be touched to a piece of No. 40 iron or German-silver wire and the length of wire between these terminals shortened to $\frac{1}{4}$ inch or less. The wire will be heated to incandescence and probably melted.

The experiment shows that in the passage of the current through the wire the energy of the electric current is transformed into heat energy. The electrical energy expended when a current flows between points of given P.D. may be spent in a variety of ways. For example, it may be spent in producing chemical separation, as in the charging of a storage cell; it may be spent in doing mechanical work, as in running an electric motor; or it may be spent wholly in heating the wire, as was the case in the experiment. It will always be expended in this last way when no chemical or mechanical changes are produced by it. (See opposite page 309.)

342. Energy relations of the electric current. We found in Chapter VII that energy expended on a water turbine is equal to the quantity of water passing through it times the difference in level through which the water falls; or, that the *power* (rate of doing work) is the product of the *fall in level* and the *current strength*. In just the same way it is found that when a current of electricity passes through a conductor, the power, or rate of doing work, is equal to the *fall in potential* between the ends of the conductor times the *strength of the electric current*. If the P.D. is expressed in volts and the current in amperes, the power is given in watts, and we have

$$\text{Volts} \times \text{amperes} = \text{watts}.$$

This is simply a result of the way in which the units are chosen. The *energy* of the electric current is usually measured in kilowatt hours.

A kilowatt hour is the quantity of energy furnished in one hour by a current whose power, or rate of expenditure of energy, is a kilowatt.

343. Amount of heat developed by a current. Since one calorie is equal to 42,000,000 ergs (§ 185), 1 watt (10,000,000 ergs per second) develops in one second .24 calories. Therefore the number of calories, H, developed in t seconds by a current of I amperes between two points whose P.D. is V volts is expressed by the equation

$$H = .24\ IVt.$$

Since from Ohm's law $V = IR$,

$$H = .24\ I^2Rt,$$

or the *heat generated in a conductor is proportional to the time, to the resistance, and to the square of the current.*

344. Incandescent lamps. The ordinary incandescent lamp (Fig. 299) consists of a tungsten filament heated to incandescence by an electric current.

Since the filament would burn up in a few seconds in air, it is placed in a highly exhausted bulb. When in use it slowly vaporizes, depositing a dark, mirrorlike coating of metal upon the inner surface of the bulb. The lead-in wires are soldered one to the base A of the socket and the other to its rim B, these being the electrodes through which the current enters and leaves the lamp. The wires w, w, sealed into the walls of the bulb, must have the same coefficient of expansion as the glass, to prevent leakage of air.

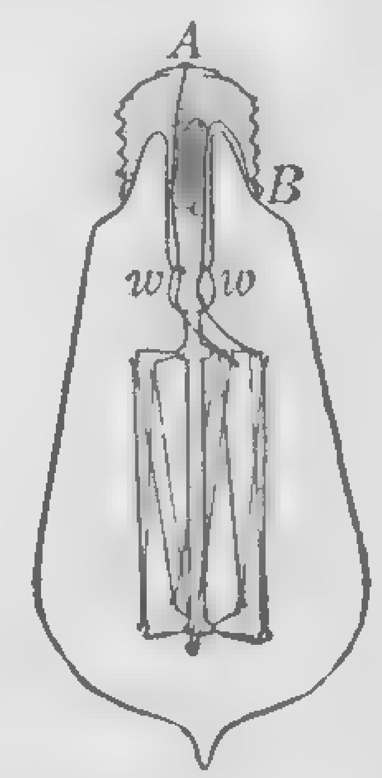
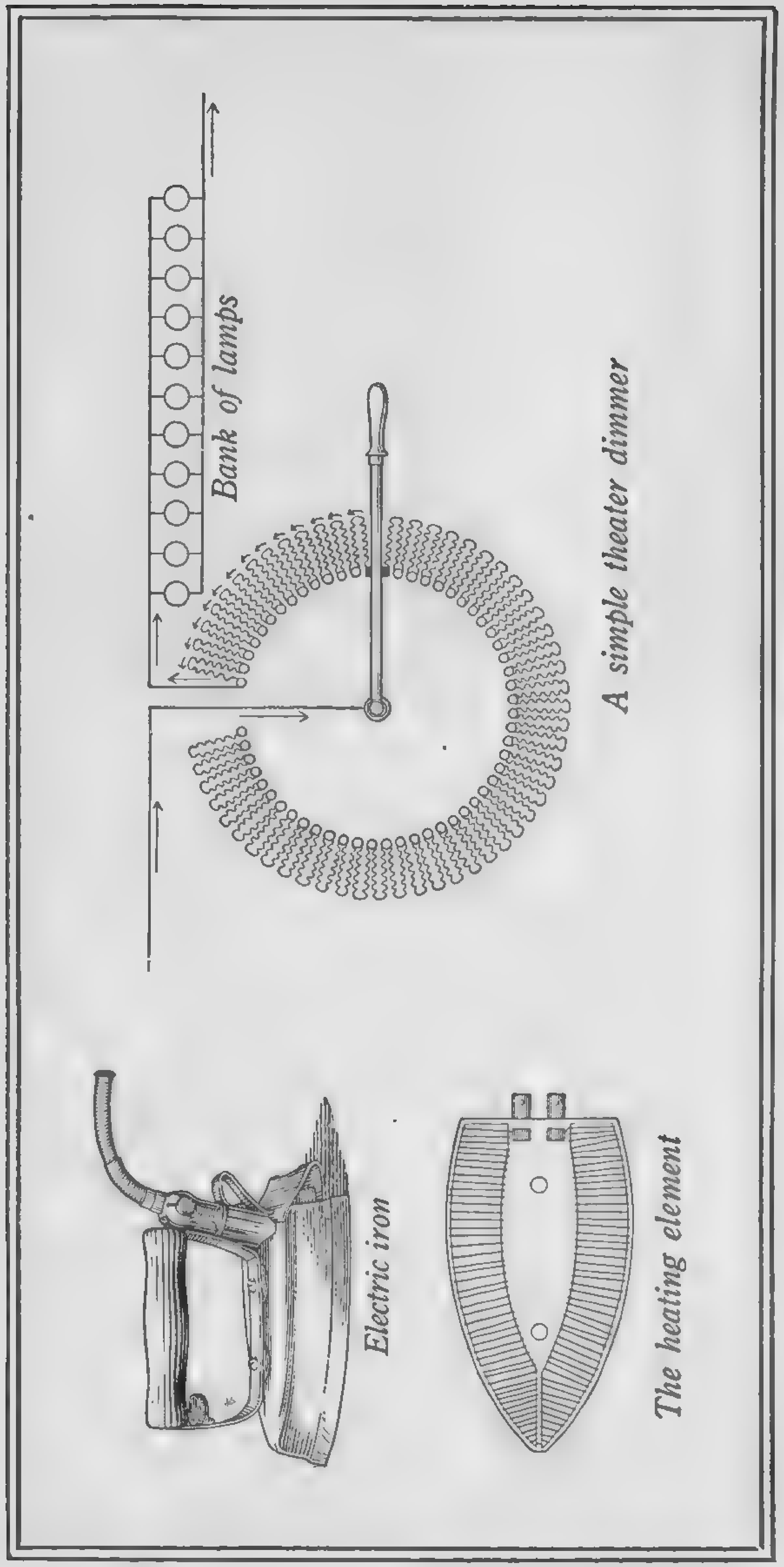


FIG. 299. The tungsten vacuum lamp

Incandescent lamps are usually grouped in parallel or multiple, on a circuit that maintains a potential of something over 100 volts between the terminals of the lamps (Fig. 321). The rate of consumption of energy is about 1.25 watts per candle power for the ordinary sizes. Tungsten filaments, being operated at a much higher temperature than is possible with the now almost obsolete carbon filament, have an efficiency nearly three times as great.

THE EARLY EDISON LAMP AND THE MODERN GAS-FILLED LAMP

In 1879 Thomas A. Edison invented a carbon-filament vacuum lamp of high resistance. To operate these lamps in parallel (the only practical method for homes) he invented a three-wire, constant-potential, generating and distributing system, by which the current was subdivided. This system is the one in use today. In 1911 Dr. William D. Coolidge, after years of work, discovered how to produce *ductile* tungsten for the manufacture of filaments, and in 1913 Dr. Irving Langmuir invented the extremely efficient, gas-filled, tungsten lamp. These two notable triumphs made the incandescent lamp supreme as the present-day illuminant, saving the public over a billion dollars on what it would have to pay if the amount of light used at this time was obtained from the obsolete carbon lamps. The picture on the left shows one of Edison's very early, commercial, carbon-filament vacuum lamps. It was placed on the market in 1880, was 7 inches long, consumed 100 watts and gave about 16 horizontal candle power, or 160 lumens. The lamp pictured on the right represents the latest development of the gas-filled, spiral-filament type. The one here shown is 6 inches long and also consumes 100 watts but gives about 132 candle power, or 1320 lumens. The gas used is argon mixed with a *small percentage of nitrogen*, since pure argon ionizes at the temperature of operation and hence creates a short circuit. The globe is smooth on the outside and frosted within, the inner irregularities being filled with a transparent medium which enables the glass to transmit practically all the light. From 6 per cent to 20 per cent of the light is absorbed by lamps frosted on the outside. There are upward of half-a-billion incandescent lamps in use in the United States, which is about half the number used by the entire world. (Courtesy of the Edison Lamp Works)



PRACTICAL USES OF RESISTANCE

Resistance devices are used to transform electrical energy into heat and to control the strength of currents. For example, electric stoves, toasters, soldering irons, water heaters, laundry irons, and fuses utilize the heating effect of the current, whereas motor starting boxes and theater dimmers are used in current control. The heating element of the iron shown in the figure consists of nickel-chromium ribbon wound upon a sheet of mica. An ordinary iron requires about 600 watts, or enough power to operate ten 60-watt lamps. The figure at the right shows the principle of resistance dimmers used in theaters

Great care must be taken to remove not only the air but traces of water vapor which adheres with great persistence to the surface of the glass. To remove this the globe is heated to at least 300° C., red phosphorus in small amount being present. A vacuum of .001 mm. is thus obtained. The life of these lamps is usually from 1000 to 2000 hours.

A customer usually pays for his light by the kilowatt hour (§ 342). The rate at which energy is consumed by a lamp carrying $\frac{1}{4}$ ampere at 100 volts is 25 watts. Two such lamps running for 4 hours would, therefore, consume $2 \times 4 \times 25 = 200$ watt hours $= .200$ kilowatt hour. The energy is measured and recorded on a *recording watt-hour meter* (Fig. 324).

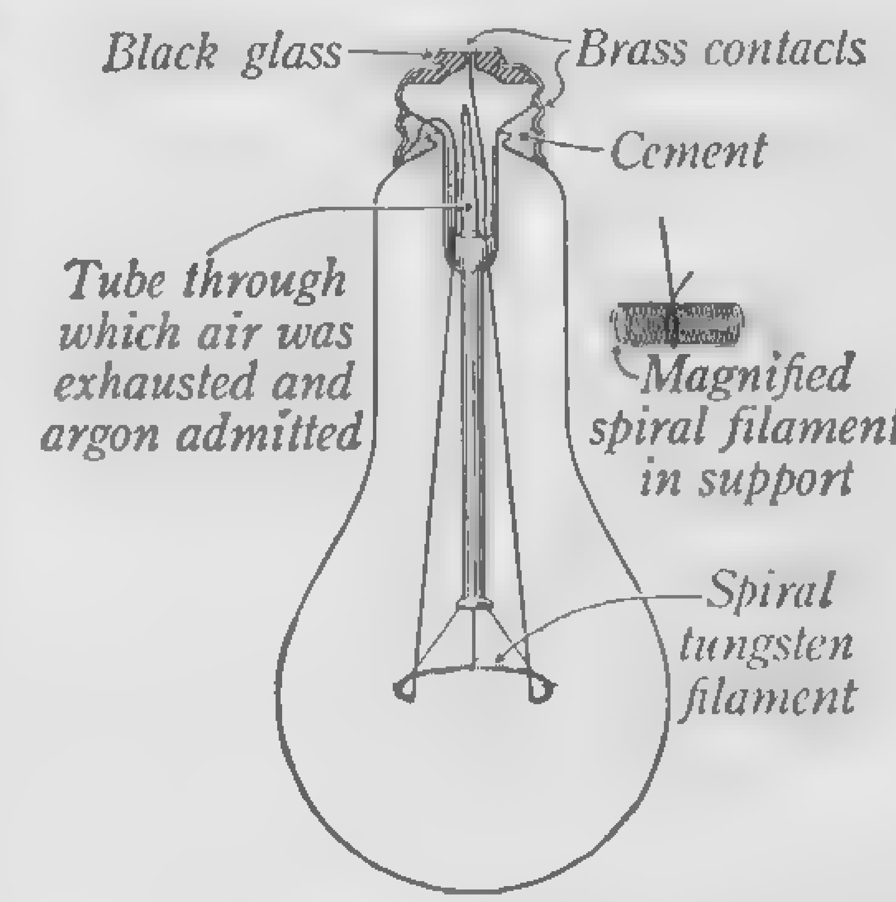


FIG. 300. Gas-filled lamp with fine spiral filament

By filling the bulb with argon a very efficient form of the tungsten lamp is obtained (Fig. 300). The long filament is wound into an exceedingly fine spiral to minimize heat radiation. As we have already learned (§ 206), the presence of gas retards evaporation; hence because of the argon the filament may be raised to 2400° C., a higher temperature than is permissible in a vacuum. A greatly increased candle power results from the slight increase in current. Moreover, the convection currents in the gas-filled lamp cause the mirror due to vaporization to form near the top of the globe, where it does not obscure the intensity of the light. The larger sizes of gas-filled lamps consume only .6 watt per candle power. (See opposite page 308.)

Today the production of incandescent lamps is enormous. Under the patents of one organization alone there are manufactured 3000 lamps every minute of every working day throughout the year.

345. The carbon arc light. When two carbon rods are placed end to end in the circuit of a powerful electric generator, the carbon about the point of contact is heated red-hot. If, then, the ends of the carbon rods are separated one-fourth inch or so, the current will still continue to flow, for a conducting layer of incandescent vapor, called an *electric arc*, is produced between the poles. The appearance of the arc is shown in Fig. 301. At the + pole a hollow, or crater, is formed in the carbon, and the – carbon becomes cone-shaped, as in the figure. The carbons are consumed at the rate of about an inch an hour, the + carbon wasting away about twice as fast as the – one. The light comes chiefly from the + crater, where the temperature is about 3700° C. (6800° F.), the highest attainable by man. All known substances are volatilized in the electric arc.

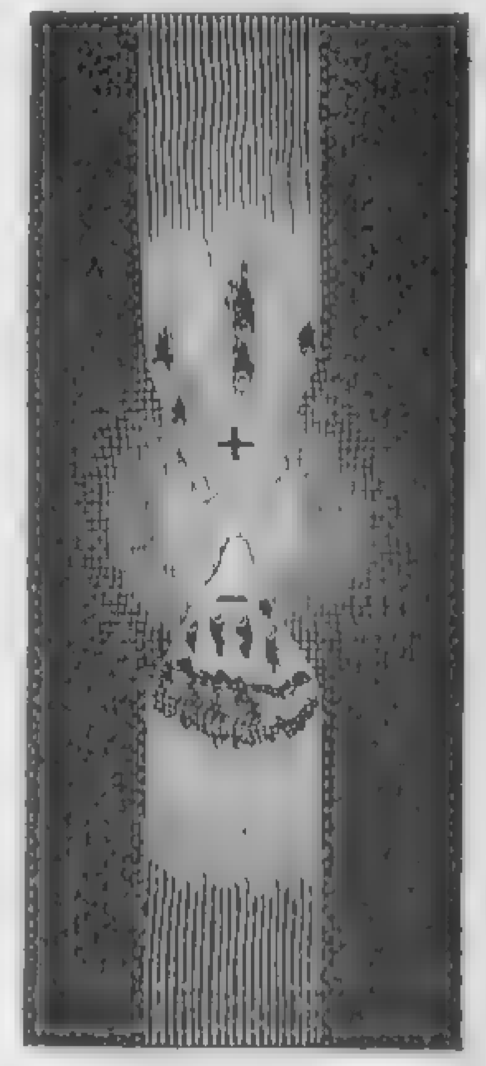


FIG. 301. The arc light

The light of the arc lamp is due to the intense heat developed on account of resistance, not to actual combustion, or burning.

The powerful and efficient arc lamp is now practically obsolete except for spot lights, moving-picture machines, and search lights.

346. The Cooper-Hewitt mercury arc lamp. The Cooper-Hewitt mercury arc lamp (Fig. 302) differs from the carbon arc lamp in that the incandescent body is a long column of mercury vapor instead of an incandescent solid. The lamp consists of an exhausted tube three or four feet long, the positive electrode at the top being a plate of iron, and the negative electrode at the bottom a small quantity of mercury. Before the lamp begins to burn, the space within it is an almost perfect vacuum, through which the difference in potential at the terminals is unable to send a current. To start the lamp the lower end is tilted upward and then immediately lowered. This

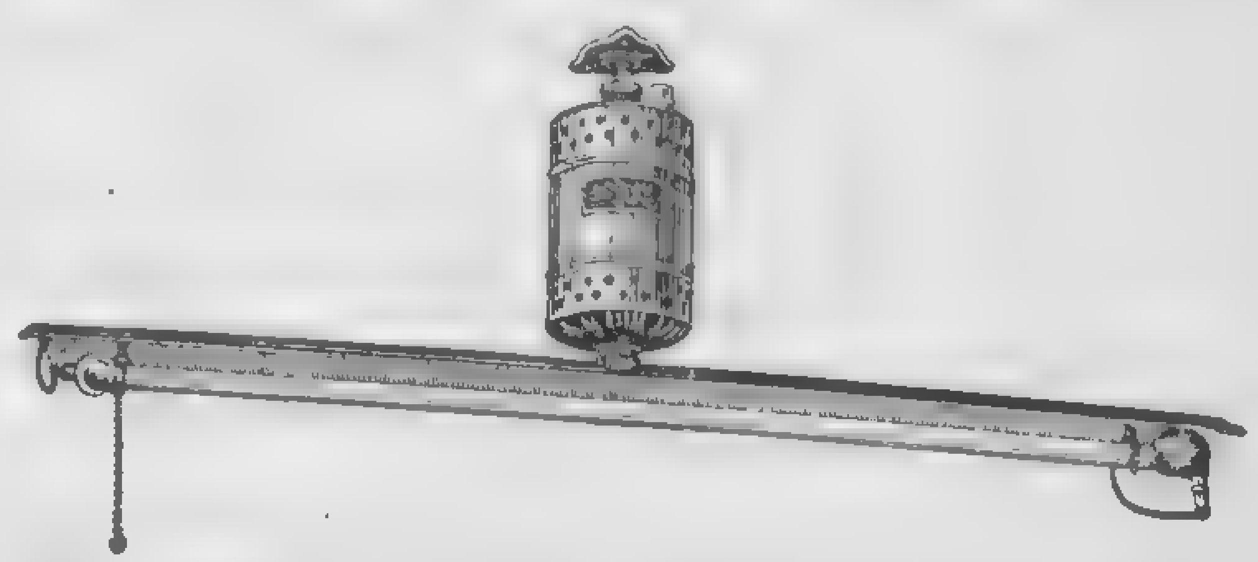


FIG. 302. The Cooper-Hewitt mercury-vapor arc lamp

forms a momentary continuous conducting column of mercury, which on breaking establishes an arc the heat of which fills the tube with the vapor of mercury. A long mercury-vapor arc is thus formed, which stretches from terminal to terminal in the tube. This arc emits a very brilliant light, but it is almost entirely wanting in red rays. The strength of its actinic rays makes it especially valuable in photography. Its commercial efficiency is about .6 watt per candle power. Cooper-Hewitt lamps having quartz tubes are used for sterilizing purposes because of the powerful ultra-violet rays which the quartz transmits.

SUMMARY. Electrical power is measured in watts (§ 145). 746 watts = 1 H. P. (§ 144). Watts = volts × amperes.

Electrical energy is measured in kilowatt hours.

The number of calories of heat developed by the electric current in any number of seconds = .24 I^2 Rt.

QUESTIONS AND PROBLEMS *

1. If an automobile storage battery has an E.M.F. of 6 volts and furnishes a momentary current of 200 amperes in starting the engine, what is its power, or rate of expenditure of energy, in watts? in kilowatts? in horse power?

2. If one of the wire loops in a tungsten lamp is short-circuited, what effect will this have on the amount of current flowing through the lamp? on the brightness of the filament? on the life of the lamp?

3. What is meant by a 104-volt lamp? What would happen to such a lamp if the P.D. at its terminals amounted to 500 volts? Trolley cars are usually furnished with current at about 500 volts; how would you use 100-volt lamps on such a circuit?

4. A 50-volt carbon lamp carrying 1 ampere has about the same candle power as a 100-volt carbon lamp carrying $\frac{1}{2}$ ampere. Explain why.

5. A very common electric lamp used in our homes is marked 25 watts and carries about $\frac{1}{4}$ ampere. One fresh dry cell on short circuit will deliver 30 or more amperes. Will the cell light the lamp? (Prove your answer is right by using the data given.)

* Supplementary questions and problems for Chapter XIV are given in the Appendix.

6. How many 25-watt incandescent lamps, connected in parallel, might be used at the same time on a 110-volt house-lighting circuit capable of furnishing a current of 10 amperes?

7. An electric flatiron taking 5 amperes from a 110-volt circuit is used for 25 min. (1) What is its resistance? (2) How many watts does it require? (3) If the rate is $.12 per kilowatt hour, what is the cost of the electrical energy used?

8. How long can you burn one 25-watt lamp in your home for a cent at $.10 per kilowatt hour?

9. A small arc lamp requires a current of 5 amperes and a difference of potential between its terminals of 45 volts. What resistance must be connected in series with it in order to use it on a 110-volt circuit?

10. The resistance of a certain water-heating coil is 20 ohms, and when connected to the house circuit it carried 5 amperes. How many minutes will it take this coil to heat 480 g. of water from 10° C. to 100° C.?

11. A certain kind of electric toaster takes 5 amperes at 110 volts. It will make two pieces of toast at once in 3 min. (1) At what horse-power rate does the toaster convert electrical energy into heat energy? (2) At $.08 per kilowatt hour what does it cost to make 12 pieces of toast?

CHAPTER XV

INDUCED CURRENTS

The Principle of the Dynamo and Motor

347. Current induced by a magnet. Let 100 or less turns of No. 22 copper wire be wound into a coil *C* (Fig. 303) about two and a half inches in diameter. Let this coil be connected into circuit with a sensitive d'Arsonval galvanometer, or even a simple detector made by suspending in a box, with No. 40 copper wire, a coil of 200 turns of No. 30 copper wire (see Fig. 311). Let the coil *C* be thrust suddenly over the *N* pole of a strong horseshoe magnet. The deflection of the pointer *p* of the galvanometer will indicate a momentary current flowing through the coil. Let the coil be held stationary over the magnet. The pointer will be found to come to rest in its natural position. Now let the coil be removed suddenly from the pole. The pointer will move in a direction opposite to that of its first deflection, showing that a reverse current is now being generated in the coil.

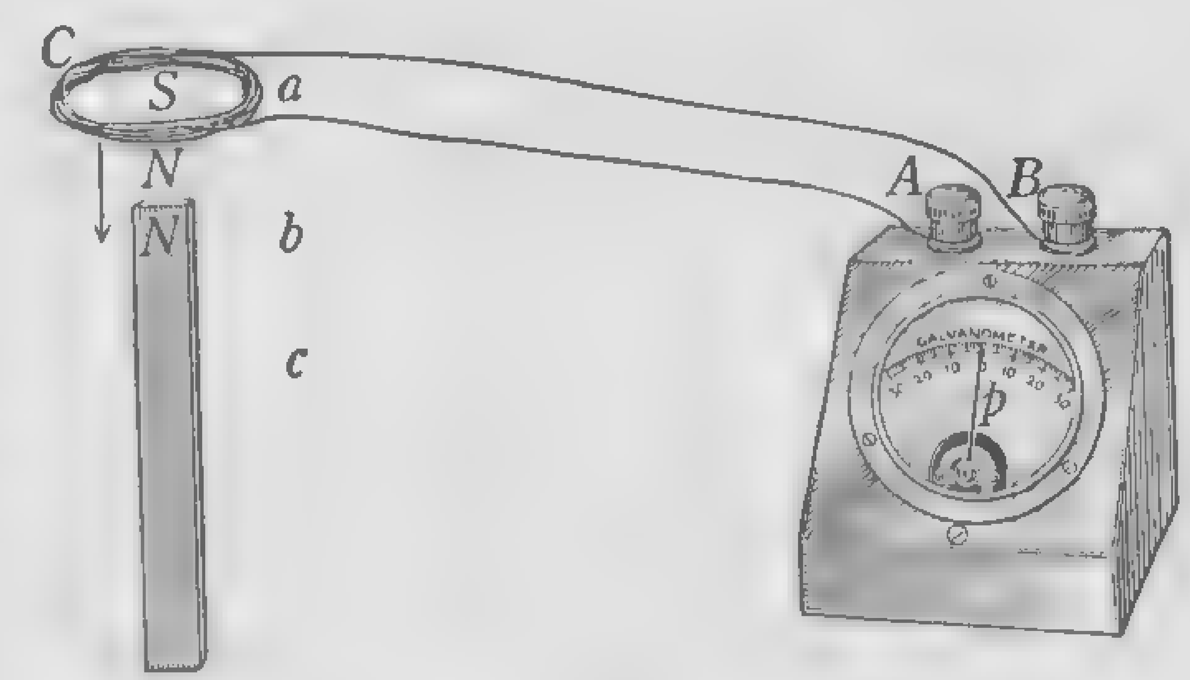


FIG. 303. Induction of electric currents by magnets

We learn, therefore, that *a current of electricity may be induced in a conductor by causing the latter to move through a magnetic field,* while a magnet has no such influence upon a conductor which is at rest with respect to the field. This discovery, one of the most important in the history of science,

was announced by the great Faraday in 1831. From it have sprung directly most of the modern industrial developments of electricity.

348. Direction of induced current. Lenz's law. In order to find the *direction* of the induced current, let a very small P.D. from a galvanic cell be applied to the terminals *A* and *B* (Fig. 303), and note the direction in which the pointer moves when the current enters, say, at *A*. This will at once show in what direction the current was flowing in the coil *C* when it was being thrust over the *N* pole. By a simple application to *C* of the right-hand rule (§ 309) we can then tell which was the *N* and which the *S* face of the coil when the induced current was flowing through it. In this way it will be found that if the coil was being thrust over the *N* pole of the magnet, the current induced in the coil was in such a direction as to make its lower face an *N* pole during the downward motion (Fig. 304, (1) and (2)), and an *S* pole during the upward motion (Fig. 304, (3) and (4)). In the first case the repulsion of the *N* pole of the magnet and the *N* pole of the coil tended to *oppose* the motion of the coil while it was moving from *a* to *b*, and the attraction of the *N* pole of the magnet and the *S* pole of the coil tended to oppose the motion while it was moving from *b* to *c*. In the second case the repulsion of the two *N* poles tended to oppose the motion from *c* to *b*, and the attraction between the *N* pole of the magnet and the *S* pole of the coil tended to oppose the upward motion from *b* to *a*. *In every case, therefore, the motion is made against an opposing force.*

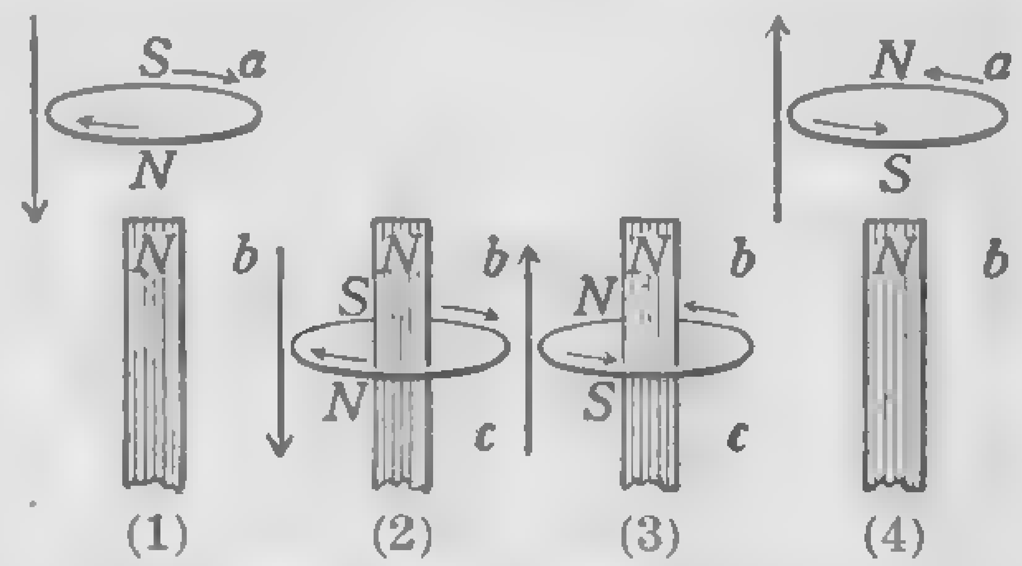
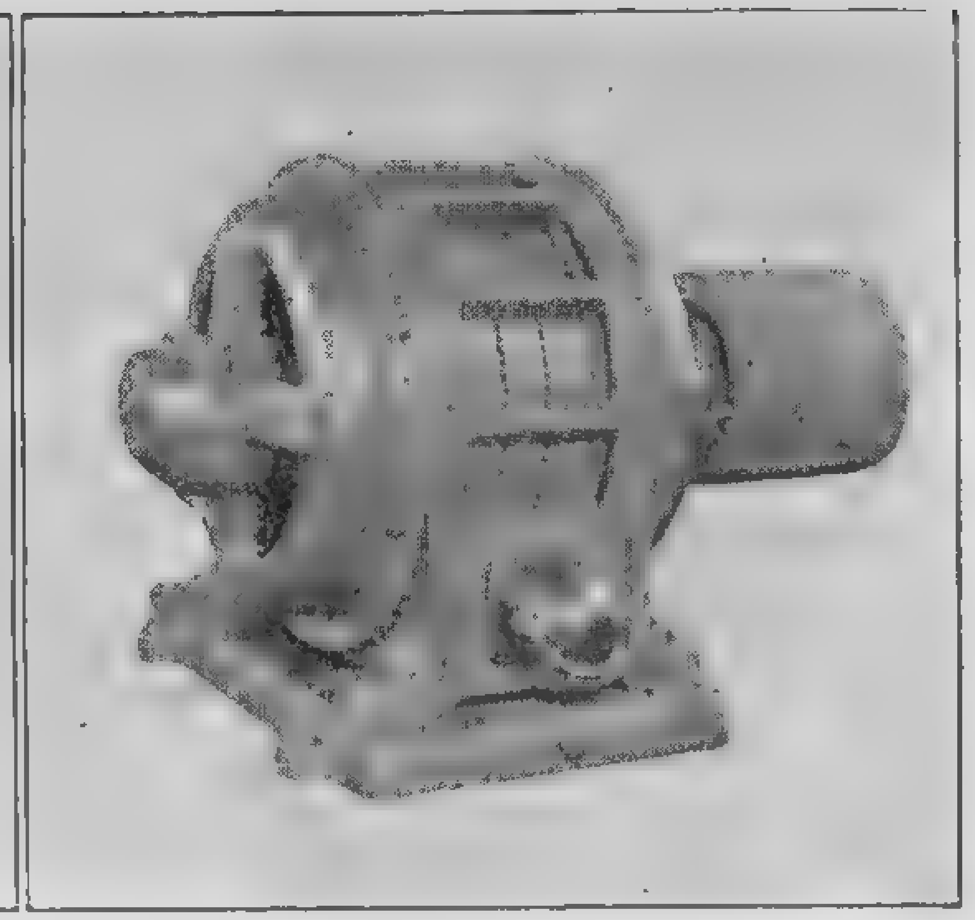


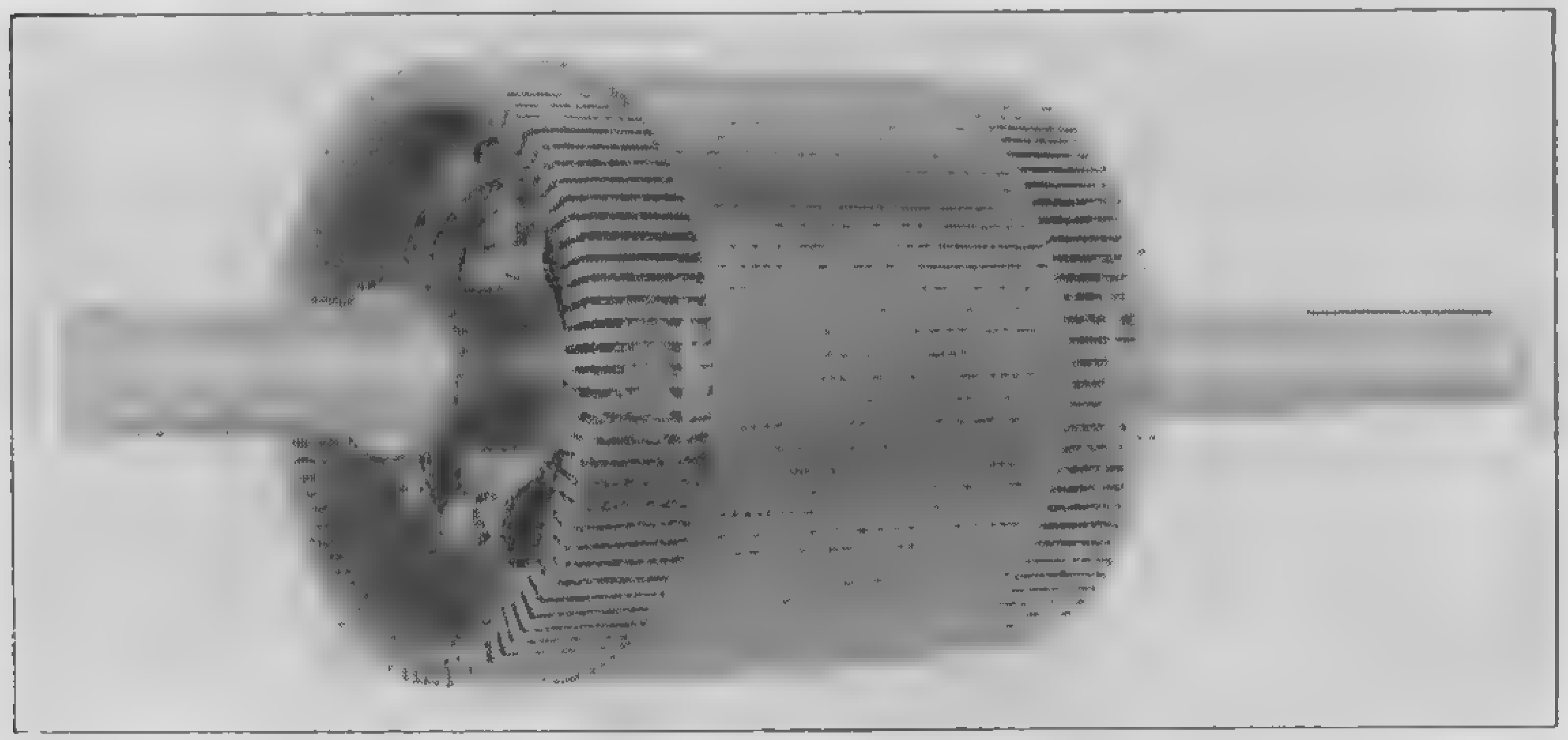
Fig. 304. Illustrating Lenz's law

From these experiments, and others like them, we arrive at the following law: *Whenever a current is induced by the relative motion of a magnetic field and a conductor, the direction of the induced current is always such as to set up a magnetic field which opposes the motion.* This is Lenz's law. This law might have been predicted at once from the principle of the conservation of energy; for this principle tells us that since an

MICHAEL FARADAY (1791–1867)

Famous English physicist and chemist and one of the most gifted of experimenters; son of a poor blacksmith; apprenticed at the age of thirteen to a London bookbinder, with whom he worked nine years; applied for a position in Sir Humphry Davy's laboratory at the Royal Institution in 1813; became director of this laboratory in 1825; discovered electromagnetic induction in 1831; made the first dynamo; discovered in 1833 the laws of electrolysis, now known as Faraday's laws. The farad, the practical unit of electrical capacity, is named in his honor





INDUCTION MOTOR

One of the most familiar of the more recent applications of the great principle of induction discovered by Faraday is the induction motor, which has come into extensive use in both large and small sizes. The particular one here shown is known as the squirrel-cage form, in which there is no electrical connection between the stator (the stationary part) and the rotor (the revolving part). The stator is wound on a laminated core like the stator of a dynamo, and the rotor consists of copper bars laid in a slotted, laminated core, their ends being joined to copper rings, one at each end. The bars are therefore in parallel. The alternating current applied to the stator windings develops a magnetic field which rotates around the iron ring of the stator. This is equivalent to a set of magnetic poles mechanically rotated around the rotor. The magnetic lines of force which therefore cut across the copper bars of the rotor generate in them an E.M.F. which causes a current to flow in the copper system of the rotor. The rotating field reacts with the field produced by the current in the conductors of the rotor so as to cause the rotor to be dragged around after the rotating field

electric current possesses energy, such a current can appear only through the expenditure of mechanical work or of some other form of energy.

349. Condition necessary for an induced E.M.F. Let the coil be held in the position shown in Fig. 305, and moved back and forth *parallel* to the magnetic field, that is, parallel to the line *NS*. No current will be induced.

By experiments of this sort it is found that an E.M.F. is induced in a coil only *when the motion takes place in such a way as to change the total number of magnetic lines of force which are inclosed by the coil.* Or, to state this rule in more general form, *an E.M.F. is induced in any element of a conductor when, and only when, that element is moving in such a way as to cut magnetic lines of force.**

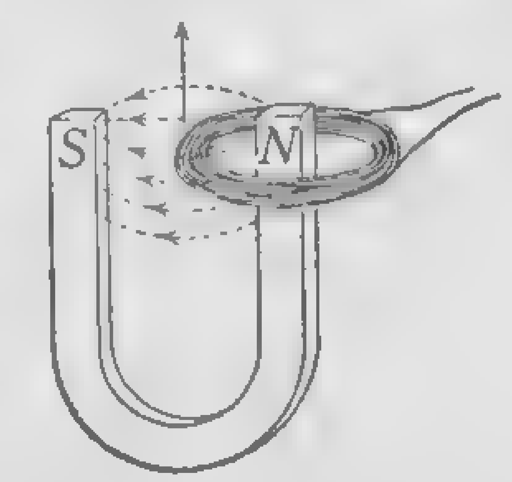


FIG. 305. Currents induced only when conductor *cuts* lines of force

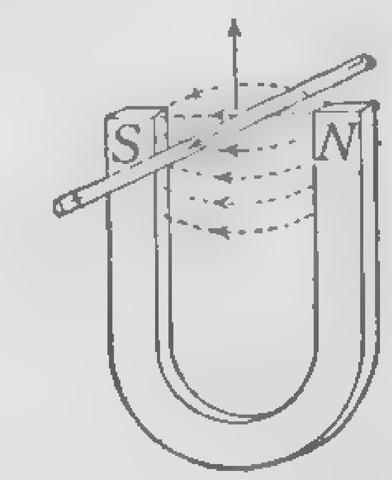


FIG. 306. E.M.F. induced whenever a straight conductor cuts magnetic lines

It will be noticed that the first statement of the rule is included in the second, for whenever the number of lines of force which pass through a coil changes, some lines of force must cut across the coil from the inside to the outside, or vice versa.

350. The principle of the electric motor. Let a vertical wire *ab* be attached rigidly to a horizontal wire *gh*, and let the latter be supported by a ring or other metallic support, in the manner shown in Fig. 307, so that *ab* is free to oscillate about *gh* as an axis. Let the lower end of *ab* dip into a trough of mercury. When a magnet is held in the position shown and a current from

* If a strong electromagnet is available, these experiments are more instructive if performed, not with a coil, as in Fig. 305, but with a straight rod (Fig. 306) to the ends of which are attached wires leading to a galvanometer. Whenever the rod moves parallel to the lines of magnetic force there will be no deflection, but whenever it moves across the lines the galvanometer needle will move at once.

a dry cell is sent down through the wire, the wire will instantly move in the direction indicated by the arrow *f*, namely, at right angles to the direction of the lines of magnetic force. Let the direction of the current in the wire be reversed. The direction of the force acting on the wire will be found to be reversed also.

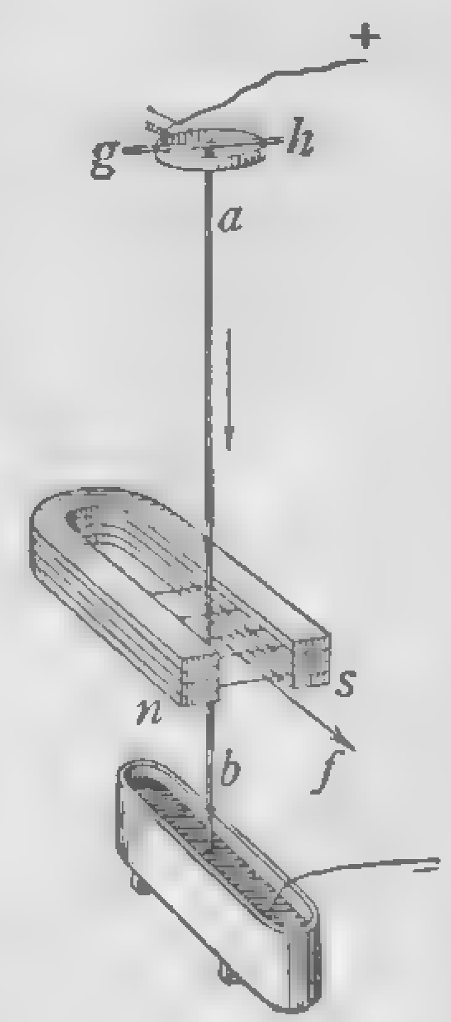


FIG. 307. The principle of the electric motor

We learn, therefore, that *a wire carrying a current in a magnetic field tends to move in a direction at right angles both to the direction of the field and to the direction of the current.* This fact underlies the operation of all electric motors.

351. The motor and dynamo rules. A convenient rule for determining whether the wire *ab* (Fig. 307) will move forward or back in a given case may be obtained as follows: If the field of a magnet alone is represented by Fig. 308, and that due to the current * alone by Fig. 309, then the resultant field when the current-bearing wire is placed between the poles of

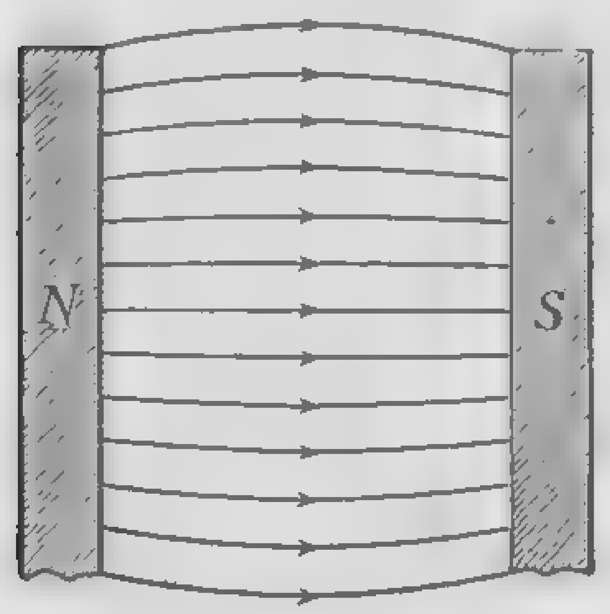


FIG. 308. Field of magnet alone

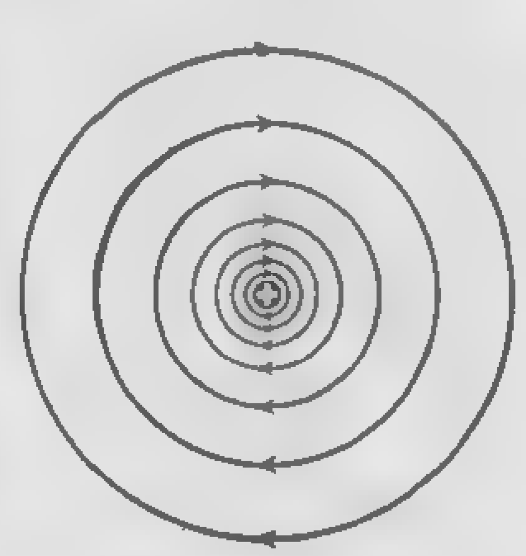


FIG. 309. Field of current alone

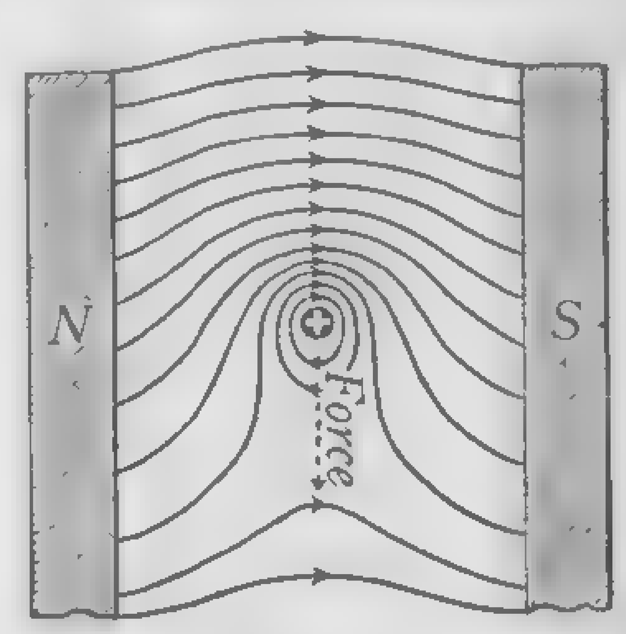


FIG. 310. Field of magnet and current

the magnet is that shown in Fig. 310; for the strength of the field above the wire is now the sum of the two separate fields,

* The cross in the conductor of Fig. 309, representing the tail of a retreating arrow, indicates that the current flows away from the reader. The dot, representing the head of an advancing arrow, indicates a current flowing toward the reader.

while the strength below it is their difference. Now Faraday thought of the lines of force as acting like stretched rubber bands. This would mean that the wire in Fig. 310 would be pushed *down. The motor rule* may be stated thus:

A current in a magnetic field tends to move away from the side on which its lines are added to those of the field.

The dynamo rule follows at once from the motor rule and Lenz's law. Thus, when a wire is moved through a magnetic field the current induced in it must be in such a direction as to oppose the motion; therefore *the induced current will be in such a direction as to increase the number of lines on the side toward which it is moving.*

352. Strength of the induced E.M.F. The strength of an induced E.M.F. is thus found to depend simply upon *the number of lines of force cut per second* by the conductor, or, in the case of a coil, upon the *rate of change* in the number of lines of force which pass through the coil. The strength of the current which flows is then given by Ohm's law; that is, it is equal to the induced E.M.F. divided by the resistance of the circuit. The number of lines of force which the conductor cuts per second may always be determined if we know the velocity of the conductor and the strength of the magnetic field through which it moves. For it will be remembered that, according to the convention of § 270, a field of unit strength is said to contain one line of force per square centimeter, a field of 1000 units strength 1000 lines per square centimeter, etc. In a conductor which is cutting lines at the rate of 100,000,000 per second there is an induced E.M.F. of 1 volt.* The reason why we used a coil of 500 turns instead of a single turn in the experiment of § 347 was that by thus making the conductor in which the current was to be induced cut the lines of force of the magnet 500 times instead of once, we obtained 500 times as strong an induced E.M.F., and therefore 500 times as strong a current for a given resistance in the circuit.

* This may be considered as *the scientific definition of the volt,* convenience alone having dictated the legal definition given in § 335.

353. Currents induced in rotating coils. Let a 400-turn or 500-turn coil of No. 28 copper wire be made small enough to rotate between the poles of a horseshoe magnet, and let it be connected into the circuit of a galvanometer, precisely as in § 347. With the coil in the position of Fig. 311 (1), let it be rotated suddenly clockwise (the observer looking down from above) through 180°. A strong deflection of the galvanometer will be observed. Let it be rotated through the next 180° back to the starting point. An opposite deflection will be observed.

The arrangement is a *dynamo* in minature. During the first half of the revolution (see Fig. 311 (2)) the wires on the right side of the loop were cutting the lines of force in one direction, while the wires on the left side were cutting them in the opposite direction. A current was being generated down on the right side of the coil and up on the left side (see dynamo rule). It will be seen that both currents flow around the coil in the same direction. The induced current is strongest when the coil is in the position shown in Fig. 311 (2), because there the lines of force are being cut most rapidly. Just as the coil is moving into or out of the position shown in Fig. 311 (1), its edges are moving *parallel* to the lines of force; hence no current is induced, since no lines of force are being cut. As the coil moves through the last 180° of its revolution both sides are cutting the same lines of force as before, but they are cutting them in an opposite direction; hence the current generated during this last half is opposite in direction to that of the first half.*

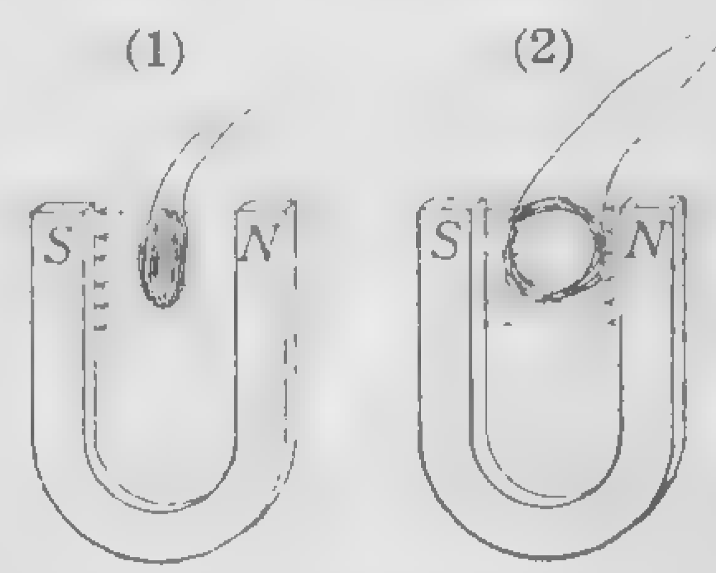


FIG. 311. Direction of currents induced in a coil rotating in a magnetic field

SUMMARY. **An induced E.M.F. is produced in a conductor when it cuts, or is cut by, magnetic lines of force.**

* A laboratory experiment on the principles of induction should be performed at about this point. See, for example, Experiment 47 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

The induced voltage is proportional to the rate of cutting of magnetic lines.

Lenz's law. **The direction of the induced E.M.F. is always such as to tend to oppose the motion (or any sort of change) producing it.**

A conductor carrying a current in a magnetic field tends to move in a direction at right angles both to the direction of the field and to the direction of the current.

The motor rule. **A current in a magnetic field tends to move away from the side on which its lines are added to those of the field.**

The dynamo rule. **The direction of the induced E.M.F. is such as to oppose the motion; that is, to thicken the magnetic lines on the side toward which the conductor is moving.**

15

QUESTIONS AND PROBLEMS

1. Can the number of lines of force within a closed coil of wire be increased or decreased without the lines being cut by the wire? Explain.

2. Under what conditions may an electric current be produced by a magnet?

3. State Lenz's law, and show how it follows from the principle of the conservation of energy.

4. A coil is thrust over the *S* pole of a magnet. Is the direction of the induced current clockwise or counterclockwise as you look down upon the pole?

5. If a coil of wire is rotated about a vertical axis in the earth's field, an alternating current is set up in it. In what position is the coil when the current changes direction?

6. How many lines of force must be cut per second to induce 10 volts?

7. A ship having an iron mast is sailing east. In what direction is the E.M.F. induced in the mast by the earth's magnetic field? If a wire is brought from the top of the mast to its bottom, no current will flow through the circuit. Why?

8. A current is flowing from top to bottom in a vertical wire. In what direction will the wire tend to move on account of the earth's magnetic field?

Dynamos

354. A simple alternating-current dynamo. The simplest form of commercial dynamo consists of a coil of wire so arranged as to rotate continuously between the poles of a powerful electromagnet (Fig. 312).

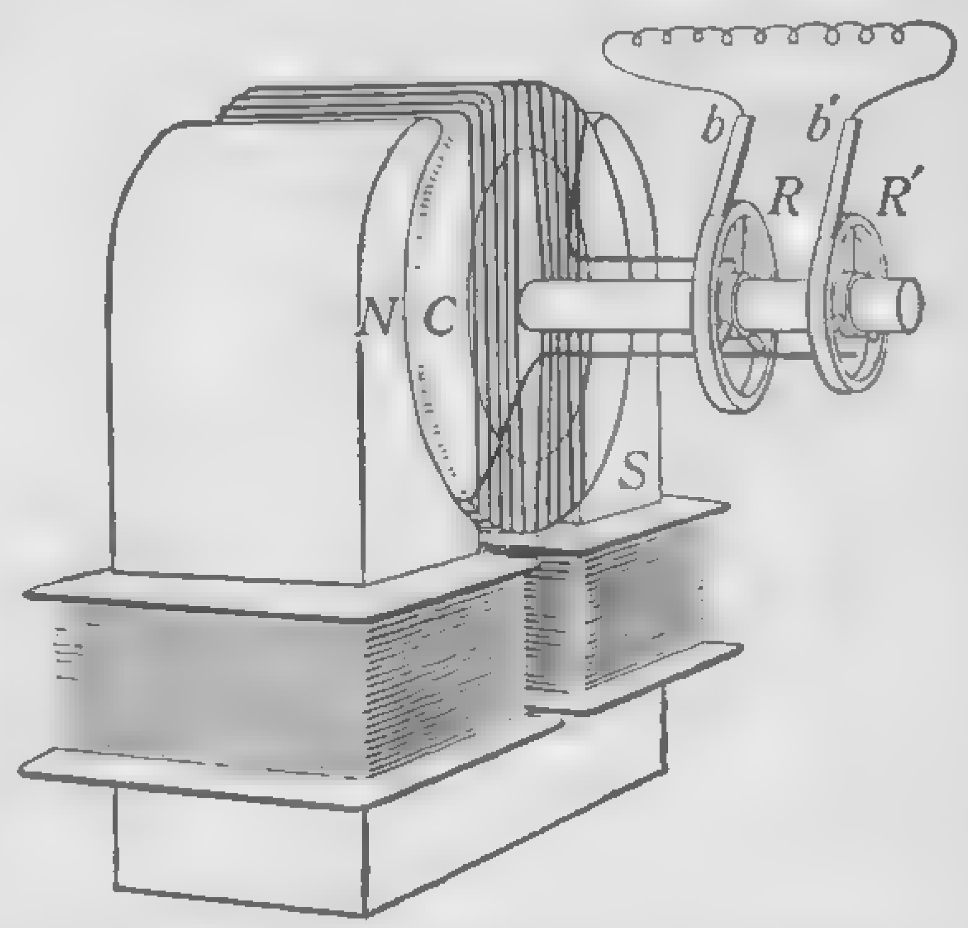


FIG. 312. Drum-wound armature

In order to make the magnetic field in which the conductor is moved as strong as possible, the coil is wound upon an iron core C. This greatly increases the total number of lines of magnetic force which pass between N and S, for instead of an air path the core offers an iron path, as shown in Fig. 313.

The rotating part, consisting of the coil with its core, is called the *armature*. One end of the coil is attached to the insulated metal ring R, which is attached rigidly to the shaft of the armature and therefore rotates with it, and the other end of the coil is attached to a second ring R'. The brushes b and b', which constitute the terminals of the external circuit, are always in contact with these rings.

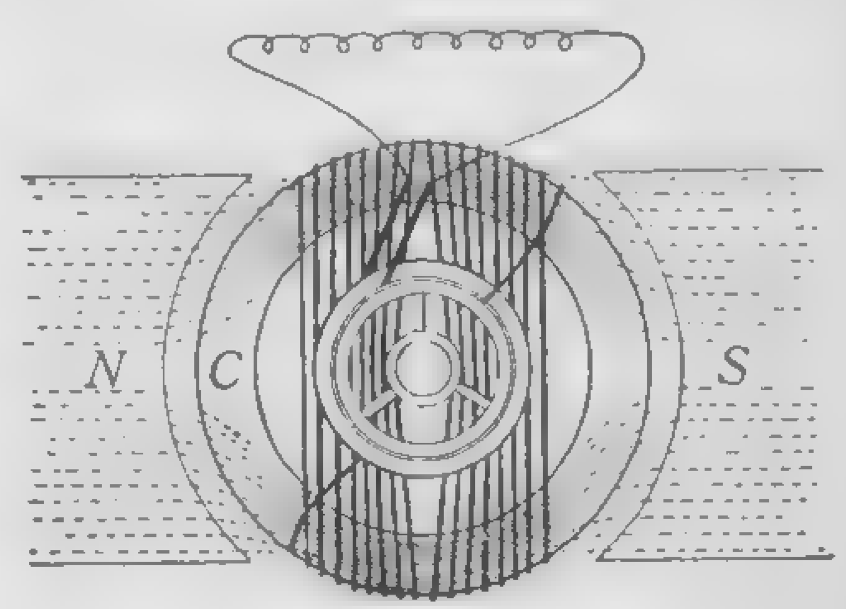


FIG. 313. End view of drum armature

As the coil is forced to rotate, an induced alternating current passes through the circuit. This current reverses direction as often as the coil passes through the position shown in Fig. 313, that is, the position in which the conductors are moving *parallel* to the lines of force; for at this instant the conductors which were moving up begin to move down, and

those which were moving down begin to move up. The current reaches its maximum value when the coils are moving through a position 90° farther on, for then the lines of force

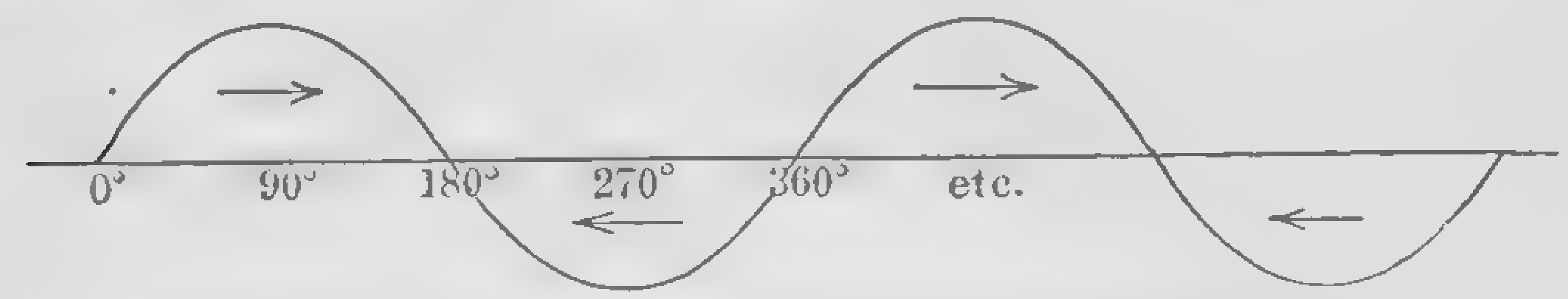


FIG. 314. Curve of alternating electromotive force

are being cut most rapidly by the conductors on both sides of the coil. These facts are graphically represented by the curve of E.M.F.'s (Fig. 314).

355. The multipolar alternator. For most commercial purposes it is found desirable to have 120 or more alternations of current per second. This could not be attained easily with two-pole machines like those sketched in Figs. 312 and 313. Hence commercial alternators are commonly built with a large number of poles alternately N and S, arranged around the circumference of a circle in the manner shown in Fig. 315. These poles are excited by a *direct* current. The dotted lines represent the direction of the lines of force through the iron. It will be seen that the coils which are passing beneath N poles have induced currents set up in them the direction of which is opposite to that of the currents which are induced in the conductors which are passing beneath the S poles. Since, however, the direction of winding of the armature coils changes between each two poles, all the inductive effects of all the poles are added in the coil and constitute at any instant one single current flowing around the complete circuit in the manner indicated by the arrows in the diagram. This current reverses direc-

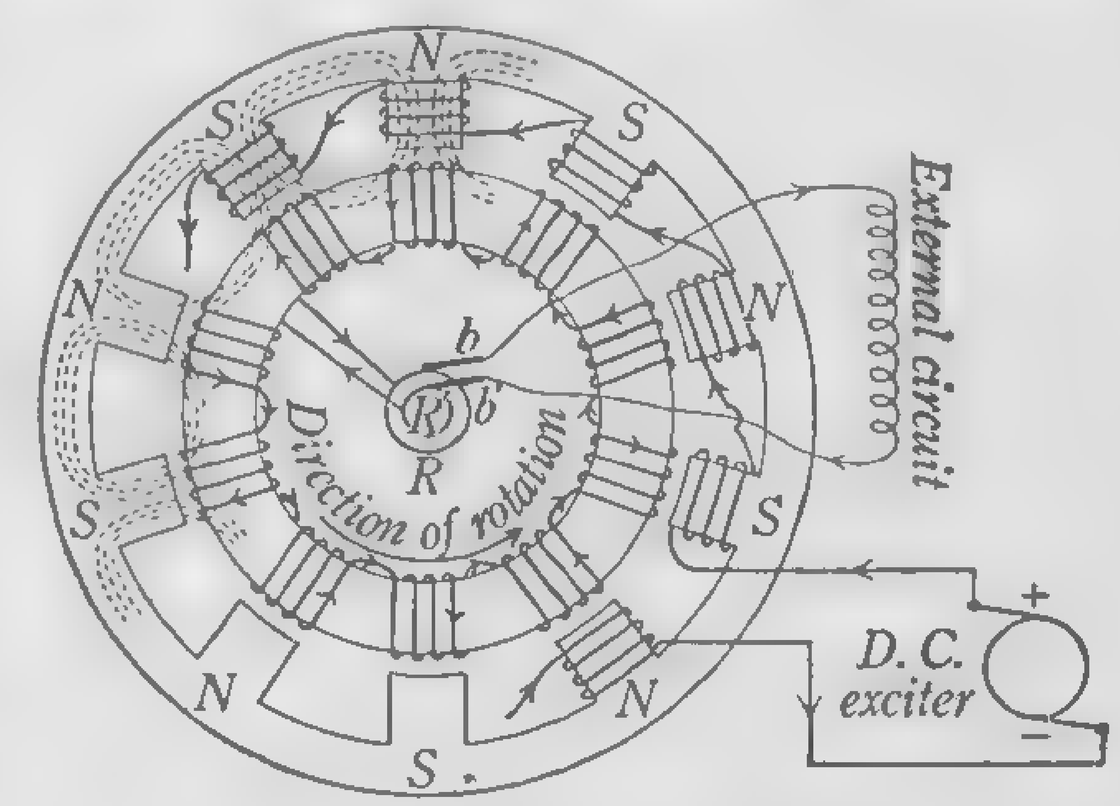


FIG. 315. Diagram of alternating-current dynamo

tion at the instant at which all the coils pass the midway points between the N and S poles. The number of alternations per second is equal to the number of poles multiplied by the number of revolutions per second. Half the number of alternations is the number of *cycles*. Fig. 314 represents four alternations, or two cycles. The number of cycles per second is called the *frequency*. The field magnets N and S of such a dynamo are usually excited by a direct current from some other source. Alternators of 5000-kilowatt capacity (nearly 7000 H.P.) have been built to run at the unusually high speed of 3600 revolutions per minute. Alternators of lower speed but of very much greater capacity are common (see opposite page 144).

356. The principle of the commutator. By the use of a so-called *commutator* it is possible to transform a current which is alternating in the coils of the armature to one which always flows in the same direction through the external portion of the circuit. The simplest possible form of such a commutator is shown in Fig. 316. It consists of a single metallic ring which is split into two equal insulated semicircular segments a and c. One end of the rotating coil is soldered to one of these semicircles, and the other end to the other semicircle. Brushes b and b' are set in such positions that they lose contact with one semicircle and make contact with the other at the instant at which the current changes direction in the armature. The current, therefore, always passes out to the external circuit through the same brush. Although a current from such a coil and commutator as that shown in the figure would always flow in the same direction through the external circuit, it would be of a pulsating rather than a steady character, for it would rise to a maximum and fall again to zero twice during each complete revolution of the armature. This effect is avoided in the com-

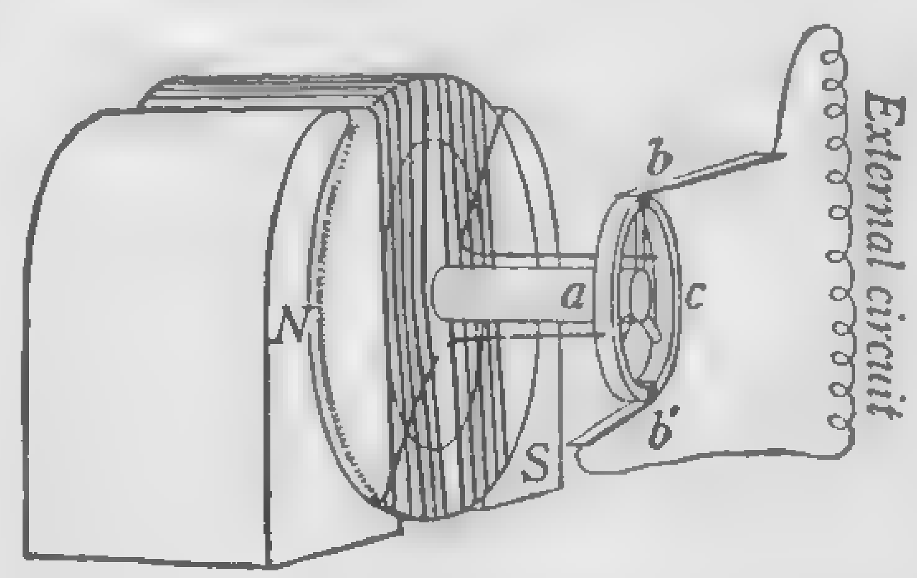


FIG. 316. The simple commutator

mercial direct-current dynamo by building a commutator of a large number of segments instead of two, and connecting each to a portion of the armature coil in the manner shown in Fig. 317. The result of using a simple split-ring commutator is shown graphically in Fig. 318.

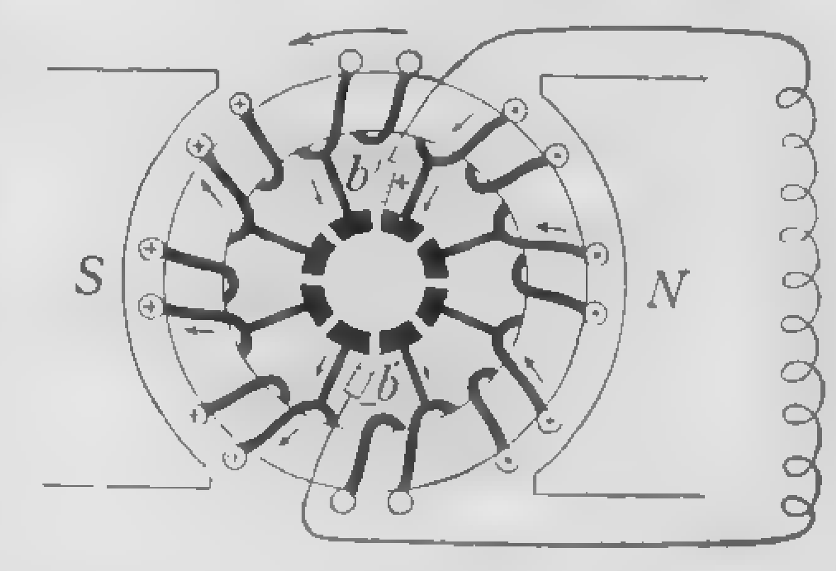


FIG. 317. Two-pole direct-current dynamo with ring armature

357. The drum-armature direct-current dynamo. Fig. 319 is a diagram showing the construction of a commercial two-pole direct-current dynamo of the drum-armature type. At a given instant currents are being induced in the same direction in all the conductors on the left half of the armature. The

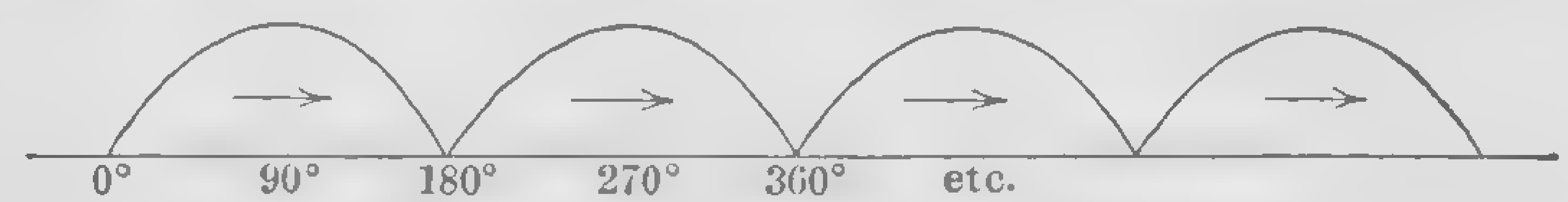


FIG. 318. Curve of commutated electromotive force

cross on each of these conductors, representing the tail of a retreating arrow, is to indicate that, while the armature is being forced to rotate counter-clockwise, these currents flow away from the reader. No E.M.F.'s are induced in the conductors at the top and bottom of the armature, where the motion is parallel to the magnetic lines. On the right half of the ring, on the other hand, the induced currents are all in the opposite direction, that is, toward the reader, since the conductors are here all being forced to move up instead of down. The dot in the middle of each of these conductors represents the head of an approaching arrow. It will be seen, however, in tracing out the connections 1, 1_1, 2, 2_1, 3, 3_1, etc. of Fig. 319 (the dotted lines representing connections at the back of the drum), that the coil is so wound about the drum that the currents in both halves

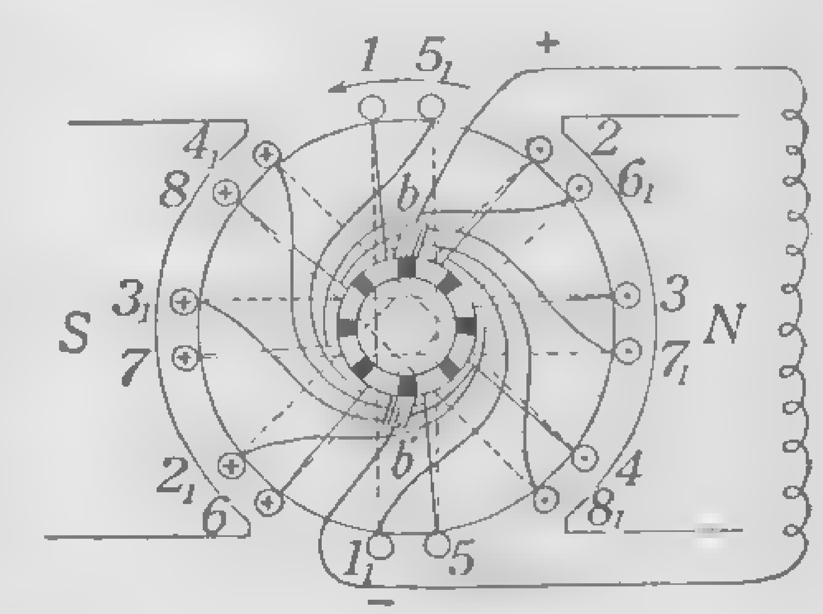


FIG. 319. The direct-current dynamo, drum winding

are always flowing toward one brush b, from which they are led to the external circuit and back at b'. This condition always exists, no matter how fast the rotation; for it will be seen that as each loop rotates into the position where the direction of its current reverses, it passes a brush and therefore at once becomes a part of the circuit on the other half of the drum, where the currents are all flowing in the opposite direction. Fig. 320 shows a typical modern four-pole generator, and in Fig. 322 may be seen more clearly the drum-wound armature. Fig. 330 (p. 335) illustrates the method of winding such an armature, each coil beginning on one segment of the commutator and ending on the adjacent segment.

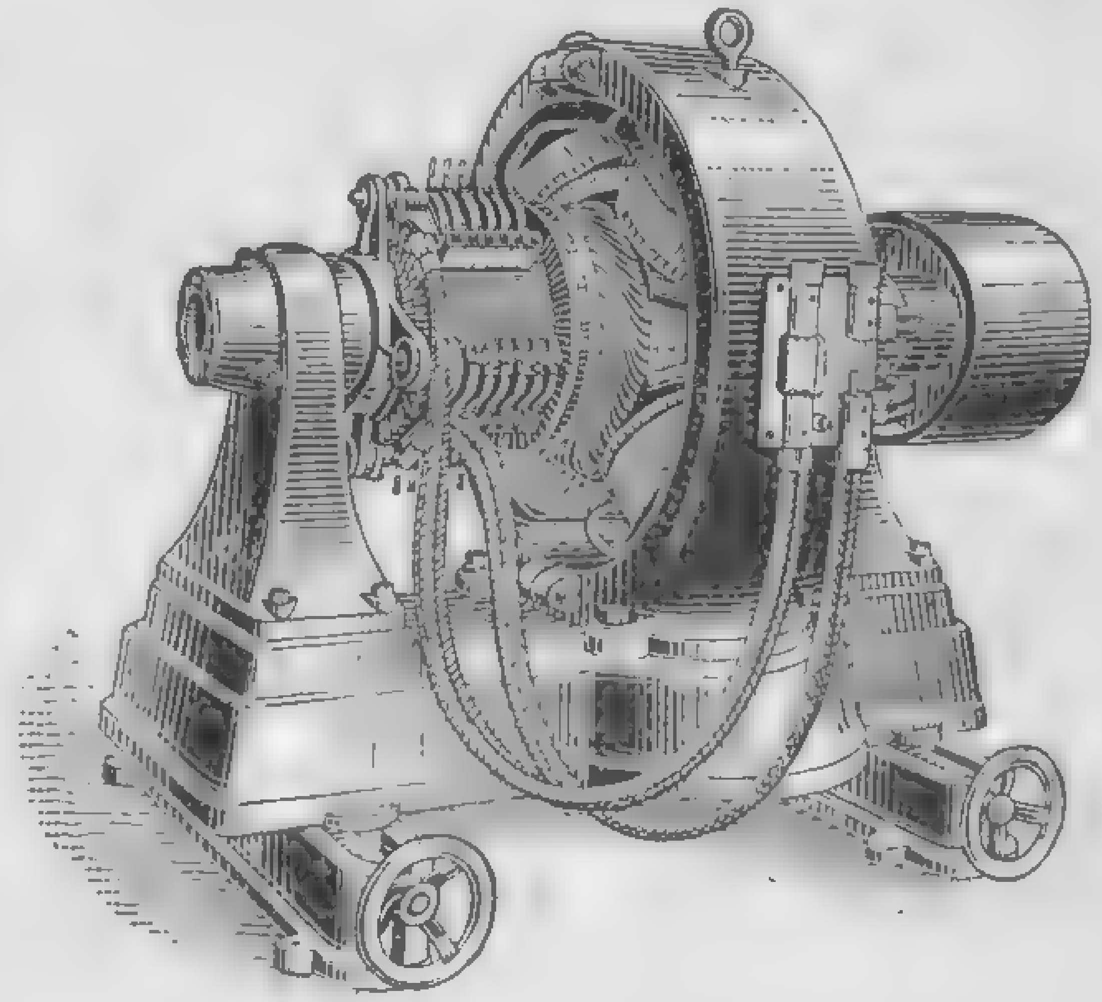


FIG. 320. A four-pole direct-current generator

358. Dynamo lighting circuit. The type of circuit generally used in D.C. incandescent lighting is shown in Fig. 321. The lamps are arranged in parallel between the mains. The field magnets are excited partly by a few series turns which carry the whole current going to the lamps, and partly by a shunt coil consisting of many turns of fine wire (Fig. 321). This combination of series and shunt winding maintains the P.D. across the mains constant for a great range of loads. Such a machine is called a *compound-wound* dynamo, to distinguish from a *series-wound* machine, for example, which dispenses with the shunt coil.

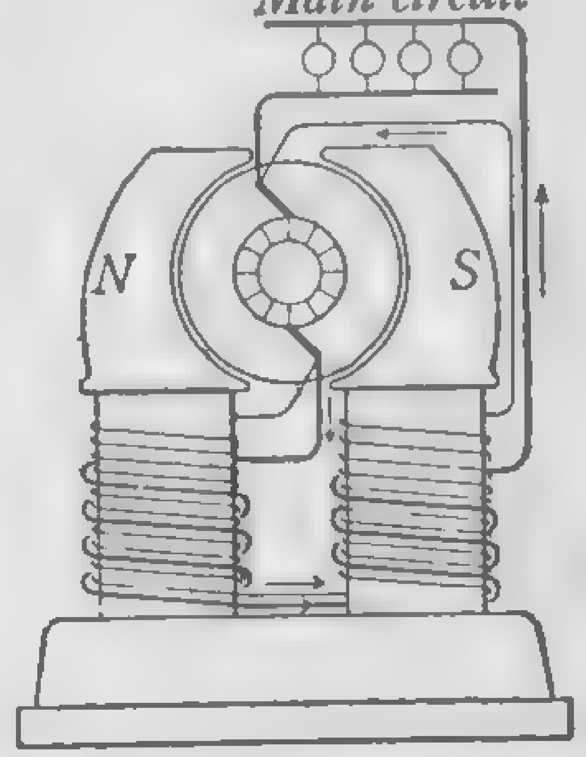
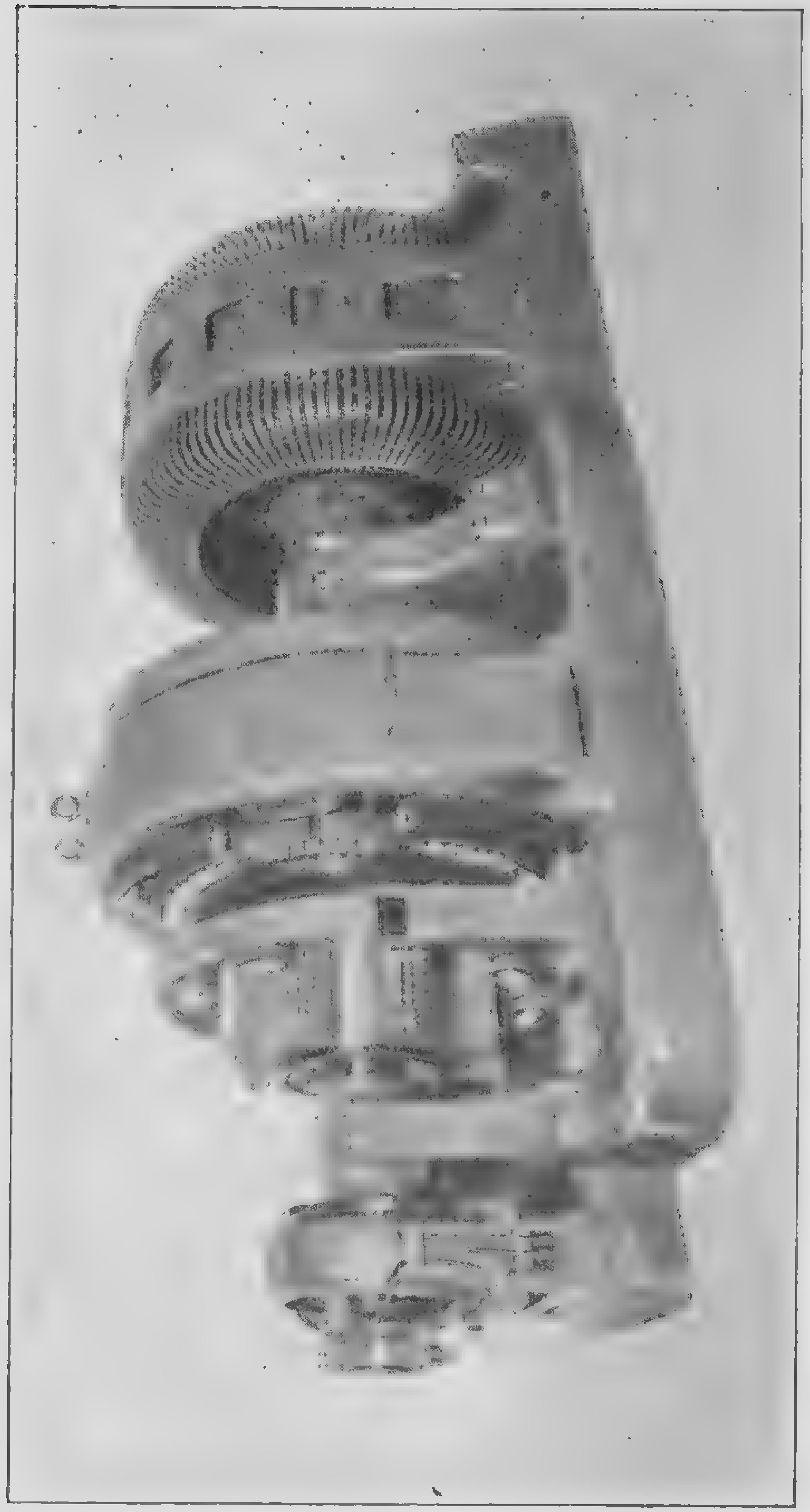


FIG. 321. The compound-wound dynamo

In all self-exciting machines there is enough residual magnetism left in the iron cores after stopping to start feeble induced currents when the machine is started up again. These currents immediately

EDISON'S FIRST ELECTRIC LOCOMOTIVE AND THE VIRGINIAN ELECTRIC

In 1880 Edison, knowing that his efficient dynamo would also operate as an efficient motor, placed one of the 12-horse-power machines on its side as shown in the picture and used it at Menlo Park to draw three cars on a narrow-gauge track one third of a mile long. The Virginian electric locomotive is the largest in the world. It is used to haul heavy trains over the Allegheny Mountains. The three parts of the locomotive make a single unit 152 feet long weighing 637.5 tons. The tractive force is 231,000 pounds, with a possible continuous horse power of 6000, reaching a maximum under certain conditions of 7125 H.P., thus exceeding in power any other locomotive in existence, either electric or steam. On going down grade the necessary braking action is obtained by allowing gravity to operate the motors as generators, thus turning power back into the transmission line to help pull other trains which are coming up grade. (Courtesy of the Westinghouse Electric and Manufacturing Company and of Thomas A. Edison)



A MOTOR-GENERATOR SET

This motor-generator set consists of an alternating-current motor (seen at the right end) which may be operated on 2300 or 4000 volts. It drives the 8-pole generator (see center) to which it is directly connected. The generator delivers direct current at 600 volts. It has a drum-wound armature, and its field is excited by a direct current from a 4-pole, 125-volt exciter mounted on the extreme left end of the shaft. Motor-generator sets similar to this one are used to furnish the current to operate electric shovels (see opposite page 120)

increase the strength of the magnetic field, and so the machine quickly builds up its current until the iron of the field magnets is brought to a state of saturation. (See opposite page 301 for a small lighting plant.)

359. The electric motor. In construction the electric motor differs in no essential respect from the dynamo. To analyze the operation as a motor of such a machine as that shown in Fig. 317, suppose a current from an outside source is first sent around the coils of the field magnets and then into the armature at b'. Here it will divide and flow through all the conductors on the left half of the ring in one direction, and through all those on the right half in the opposite direction. Hence, in accordance with the motor rule, all the conductors on the left side are urged upward by the influence of the field, and all those on the right side are urged downward. The armature will therefore begin to rotate clockwise and this rotation will continue as long as the current is sent in at b' and out at b; for as fast as coils pass either b or b' the direction of the current flowing through them changes, and therefore the direction of the force acting on them changes. The commutator keeps these conditions always fulfilled. The left half is therefore always urged up and the right half down. The greater the strength of the current, the greater the force acting to produce rotation.

If the armature is of the drum type (Fig. 319), the conditions are not essentially different; for, as may be seen by following out the windings, the current entering at b' will flow through all the conductors on the left half in one direction and through those on the right half in the opposite direction. (The *induction* motor is pictured and described opposite page 315.)

The electric motor is a device which receives electrical energy and converts it into mechanical energy. The dynamo is a device which receives mechanical energy from a steam engine, water wheel, or other source and converts it into electrical energy.

360. Street-car motors. Electric street cars are nearly all operated by direct-current series-wound motors placed under the cars and attached by gears to the axis. Fig. 322 shows a typical four-pole street-car motor. The two upper field poles are raised with the case when the motor is opened for inspection, as in the figure. The current is generally supplied by compound-wound dynamos which maintain a constant potential of about 500 volts between the trolley or third rail and the track which is used as the return circuit.

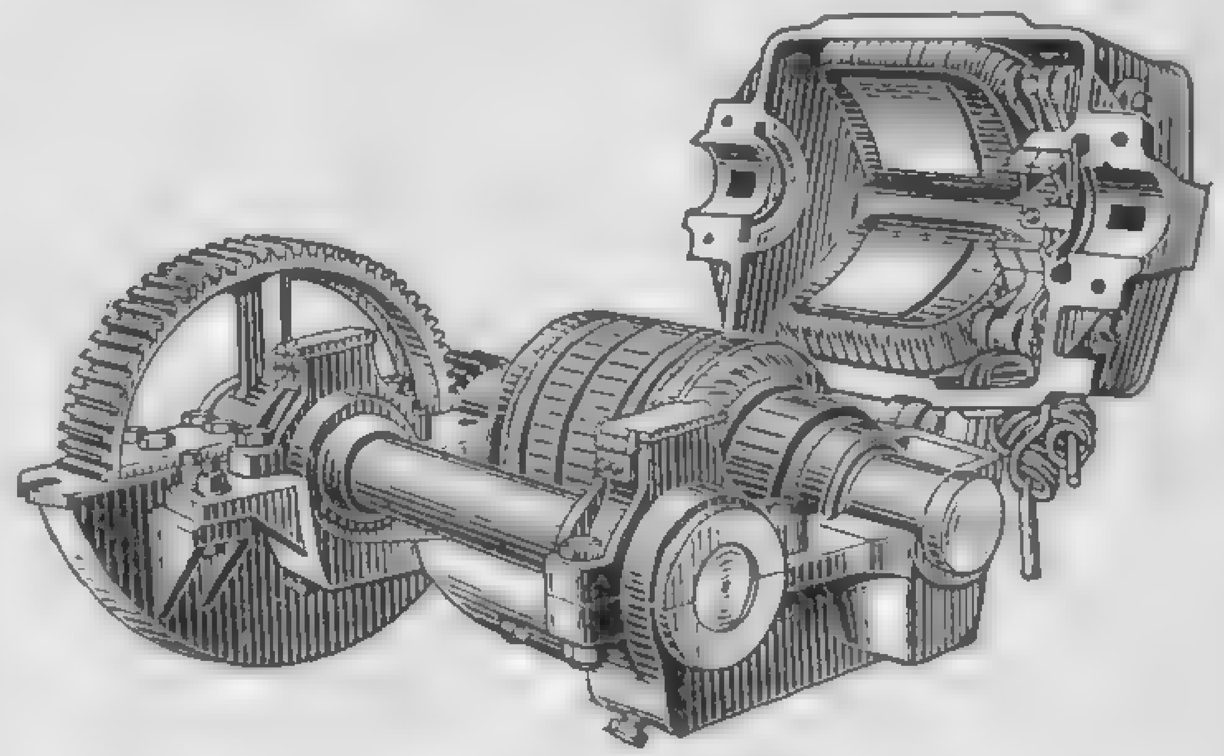


FIG. 322. Railway motor, upper field raised

The cars are always operated in parallel, as shown in Fig. 323. In a few instances street cars are operated upon alternating, instead of upon direct-current, circuits. In such cases the motors are essentially the same as direct-current series-wound motors; for since in such a machine the current must reverse in the field magnets at

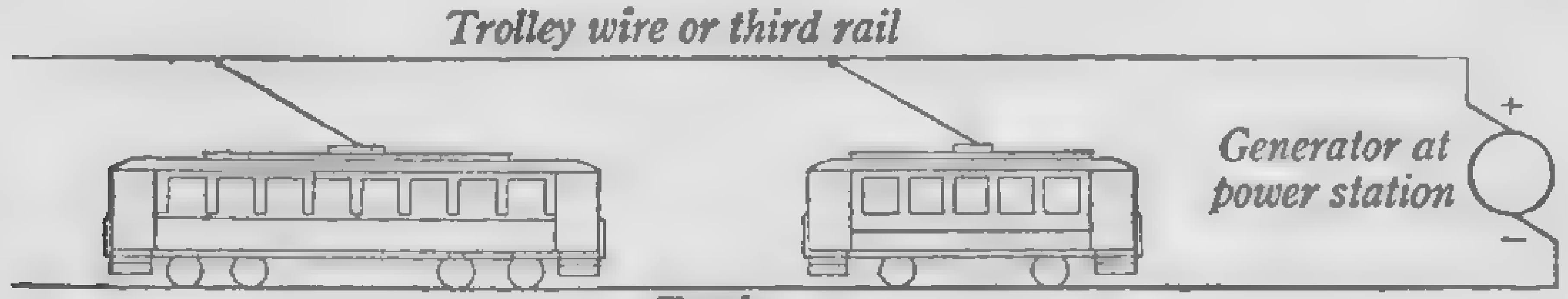


FIG. 323. Street-car circuit

the same time that it reverses in the armature, it will be seen that the armature is always impelled to rotate in one direction, whether it is supplied with a direct or with an alternating current. Other types of A.C. motors are not well adapted to starting with full load.

361. Back E.M.F. in motors. Group from four to six 100-watt lamps in parallel and then connect the group in series with a motor of, say, $\frac{1}{10}$ horse power (the familiar 75-watt demonstration school dynamo will serve the purpose, if used as a motor.) Attach to the house circuit. As the speed of rotation of the motor increases, the lamps grow dim. If the motor is now slowed by friction at the pulley wheel, the lamps grow brighter.

We learn, therefore, that the greater the speed of the motor, the less the current passing through it. When an armature is set into rotation by sending a current from some outside source through it, its coils move through a magnetic field as truly as if the rotation were produced by a steam engine, as is the case in running a dynamo. An induced E.M.F. is therefore set up by this rotation. In other words, while the machine is acting as a motor it is also acting as a dynamo. The direction of the induced E.M.F. due to this dynamo effect will be seen, from Lenz's law or from a consideration of the dynamo and motor rules, to be opposite to the outside P.D., which is causing current to pass through the motor. The faster the motor rotates, the faster the lines of force are cut, and hence the greater the value of this so-called *back E.M.F.* If the motor were doing no work, the speed of rotation would increase until the back E.M.F. reduced the current to a value simply sufficient to overcome friction. It will be seen, therefore, that, in general, the faster the motor goes, the less the current which passes through its armature, for this current is always due to the *difference* between the P.D. applied at the brushes — 500 volts in the case of trolley cars — and the back E.M.F. When the motor is starting, the back E.M.F. is zero; and hence, if the full 500 volts were applied to the brushes, the current sent through would be so large as to ruin the armature through overheating. To prevent this motors are furnished with a *starting box*, consisting of resistance coils which are thrown into series with the motor on starting, and thrown out again gradually as the speed increases and the back E.M.F. rises.* Trolley cars are usually run by two motors which, on starting, work in series, so that each supplies a part of the starting resistance for the other. After speed is acquired, they work in parallel. This is a more economical method than starting-box control.

* This discussion should be followed by a laboratory experiment on the study of a small electric motor or dynamo. See, for example, Experiments 48 and 49 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

362. The recording watt-hour meter. The recording watt-hour meter (Fig. 324) is the instrument which fixes our electric-light bills. It is essentially an electric motor containing no iron, so that the current through the armature *A* is proportional to the P.D. between the mains, while the current through the field magnets *F* is the current flowing into the house. Therefore the force acting between *A* and *F*, or the turning power on *A* (torque), is proportional to the product of volts by amperes; that is, it is proportional to the watts consumed. The rate of rotation is made slow by the magnetic drag due to the reaction between the magnets *M* and the current induced in the rotating aluminum disk *D* which rotates between the poles of the magnets. The recording dials, which are connected to the worm gear *G*, have therefore a speed which is proportional to the *watts* used, and their total rotation is proportional to the total energy, or *watt hours*, consumed. (Let the pupil examine the watt-hour meter in his home.)

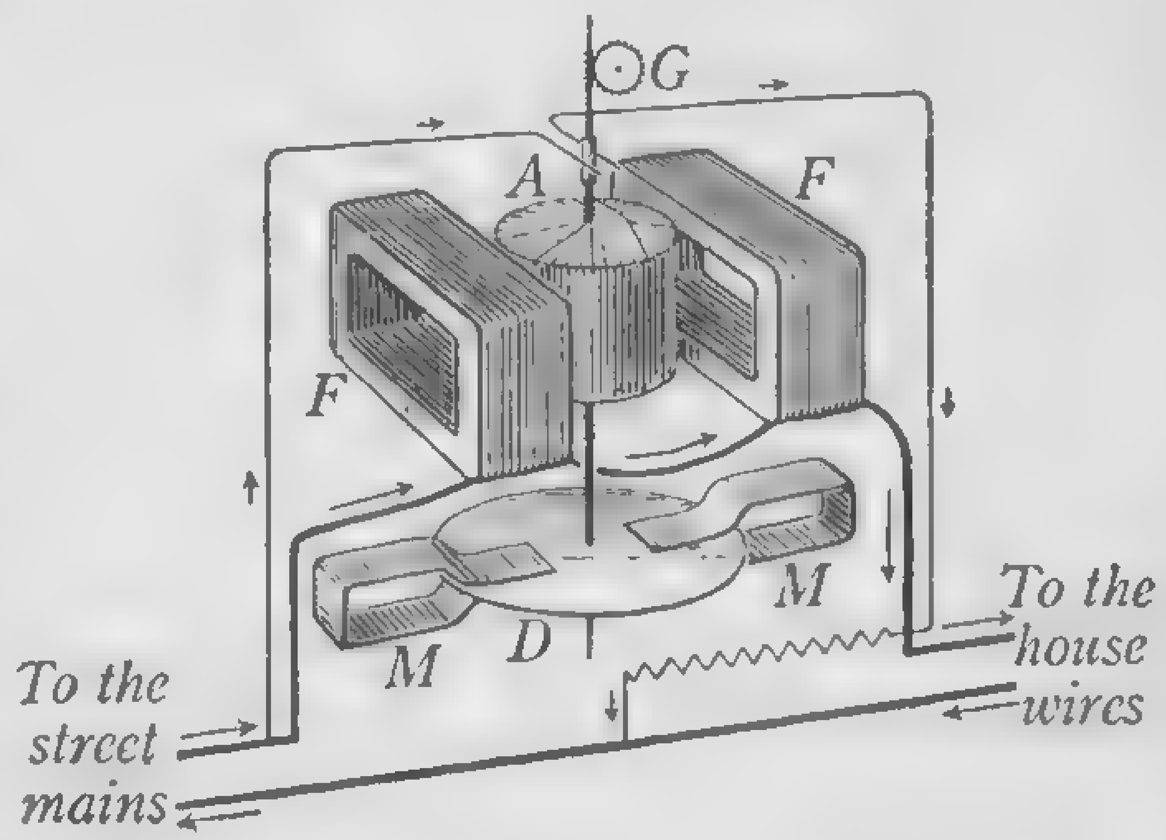


FIG. 324. Interior of a watt-hour meter

SUMMARY. A dynamo generates E.M.F. through mutual cutting of conductors and lines of magnetic force. It transforms mechanical energy into electrical energy.

An electric motor is essentially the same in construction as a dynamo. It transforms electrical energy into mechanical work.

The commutator of a dynamo is for the purpose of allowing the alternating current in the armature to come as a direct current into the external circuit.

Back E.M.F. is always generated in a motor in accord with Lenz's law.

A watt-hour meter is constructed to rotate at a speed proportional to the kilowatts, or power, used. It can, therefore, be calibrated in kilowatt hours (energy consumed).

QUESTIONS AND PROBLEMS

1. (1) What are the essential parts of an alternating-current generator? (2) Describe its operation. (3) Does it create electrical energy? (4) Give reason for your answer.

2. What is the function (use) of the field magnet of a dynamo? Wood is cheaper than iron; why are not the field cores made of wood?

3. Will it take more work to rotate a dynamo armature when the circuit is closed than when it is open? Why?

4. Explain how an alternating current in the armature is transformed into a unidirectional current in the external circuit.

5. What is the essential difference in construction between a direct-current and an alternating-current dynamo?

6. Two successive coils on the armature of a multipolar alternator are cutting lines of force which run in opposite directions. How does it happen that the currents generated flow through the wires in the same direction? (Fig. 315.)

7. Explain the process of *building up* in a dynamo.

8. How would it affect the voltage of a dynamo to increase the speed of rotation of its armature? Why? to increase the number of turns of wire in the armature coils? Why? to increase the strength of the magnetic field? Why?

9. When a wire is cutting lines of force at the rate of 100,000,000 per second, there is induced in it an E.M.F. of one volt. A certain dynamo armature has 50 coils of 5 loops each and makes 600 revolutions per minute. Each wire cuts 2,000,000 lines of force twice in a revolution. What is the E.M.F. developed?

10. Make a diagram of the two wires leading out from a generator and indicate the usual manner of attaching commercial incandescent lamps to these wires.

11. Single dynamos often operate as many as 10,000 incandescent lamps at 110 volts. If these lamps are all arranged in parallel

and each requires a current of .5 ampere, what is the total current furnished by the dynamo? What is the activity of the machine in kilowatts and in horse power?

12. How many 110-volt lamps like those of problem 11 can be lighted by a 12,000-kilowatt generator?

13. Why does it take twice as much work to keep a dynamo running when 1000 lights are on the circuit as when only 500 are turned on?

14. A direct-current generator operating at 500 volts furnishes to a factory a current of 50 amperes through a line having a resistance of 2 ohms. (1) How much power is developed by the generator? (2) At what voltage does the factory receive its current?

15. What does the commutator of a dynamo do? What is the purpose of the commutator of a motor?

16. Explain why a series-wound motor can run on either a direct or an alternating circuit.

17. An ammeter in circuit with a small motor indicates 7 amperes when the motor is starting and 3.5 amperes when the motor is running at full speed. Explain.

18. If the pressure applied at the terminals of a motor is 500 volts, and the back pressure, when running at full speed, is 450 volts, what is the current flowing through the armature, its resistance being 10 ohms?

19. An electric motor developed 2 H.P. when taking 16.5 amperes at 110 volts. Find the efficiency of the motor. (One horse power = 746 watts.)

20. The resistance of the wire connecting a generator to a motor is .05 ohm; the generator can deliver 200 amperes. (1) What is the fall in potential between the generator and the motor? (2) How many watts are expended in sending the current through the wire?

21. An electric motor having an efficiency of 85 per cent develops 3 H.P. when connected to a 220-volt circuit. How much current flows through the motor?

22. Name two uses and two disadvantages of mechanical friction; of electrical resistance.

Principle of the Induction Coil and Transformer

363. Currents induced by varying the strength of a magnetic field. Let about 500 turns of No. 28 copper wire be wound around one end of an iron core, as in Fig. 325, and connected to the circuit of a galvanometer G. Let about 500 more turns be wrapped about another portion of the core and connected into the circuit of two dry cells. When the key K is closed, the deflection of the galvanometer will indicate that a temporary current has been induced in one direction through the coil s; and when it is opened, an equal but opposite deflection will indicate an equal current flowing in the opposite direction.

The experiment illustrates the principle of the induction coil and the transformer. The coil p, which is connected to the source of the current, is called the *primary coil*, and the coil s, in which the currents are induced, is called the *secondary coil*. Causing lines of force to spring into existence inside of s (in other words, magnetizing the space inside of s) has caused an induced current to flow in s; and demagnetizing the space inside of s has also induced a current in s in accordance with the general principle stated in § 349, that *any change in the number of magnetic lines of force which thread through a coil induces a current in the coil.* We may think of the lines as always existing as closed loops (see Fig. 262, p. 275) which collapse upon demagnetization to mere double lines at the axis of the coil. Upon magnetization one of these two lines springs out, cutting the encircling conductors and inducing a current.

Fig. 325. Induction of current by magnetizing and demagnetizing an iron core

364. Direction of the induced current. Lenz's law, which, it will be remembered, followed from the principle of conservation of energy, enables us to predict at once the direction of the induced currents in the above experiments; and an observation of the deflections of the galvanometer enables us to verify the correctness of the predictions. Consider first the

case in which the primary circuit is *made* and the core thus magnetized. According to Lenz's law the current induced in the secondary circuit must be in such a direction as to *oppose the change* which is being produced by the primary current, that is, in such a direction as to tend to magnetize the core oppositely to the direction in which it is being magnetized by the primary. This means, of course, that the induced current in the secondary must encircle the core in a direction opposite to the direction in which the primary current encircles it. We learn, therefore, that *on making the current in the primary the current induced in the secondary is opposite in direction to that in the primary.*

When the current in the primary is *broken,* the magnetic field created by the primary tends to die out. Hence, by Lenz's law, the current induced in the secondary must be in such a direction as to tend to oppose this process of demagnetization, that is, in such a direction as to magnetize the core in the same direction in which it is magnetized by the decaying current in the primary. Therefore, *at break the current induced in the secondary is in the same direction as that in the primary.*

365. E.M.F. of the secondary. If half of the 500 turns of the secondary s (Fig. 325) are unwrapped, the deflection will be found to be just half as great as before. Since the resistance of the circuit has not been changed, we learn from this that *the E.M.F. of the secondary is proportional to the number of turns of wire upon it,* — a result which followed also from § 352. If, then, we wish to develop a very high E.M.F. in the secondary, we have only to make it of a very large number of turns of fine wire.

366. Self-induction. If, in the experiment illustrated in Fig. 325, the coil s had been made a part of the same circuit as p, the E.M.F.'s induced in it by the changes in the magnetism of the core would of course have been just the same as above. In other words, when a current starts in a coil, the magnetic field which it itself produces tends to induce a current opposite in direction to that of the starting current, that

is, tends to oppose the starting of the current; and when a current in a coil stops, the collapse of its own magnetic field tends to induce a current in the same direction as that of the stopping current, that is, tends to oppose the stopping of the current. This means merely that *a current in a coil acts as though it had inertia, and opposes any attempt to start or stop it.* This inertia-like effect of a coil upon itself is called *self-induction.*

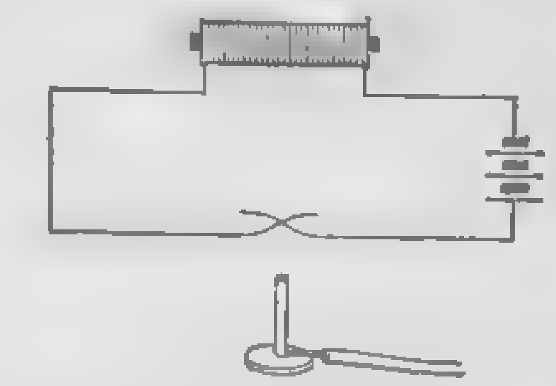


FIG. 326. Spark from self-induction

Let a few dry cells be placed in a circuit containing a coil of a large number of turns of wire wound upon iron (Fig. 326), the circuit being closed at some point by touching two bare copper wires together. Holding the bare wire in the fingers, break the circuit between the hands and observe the shock caused by the current which the E.M.F. of self-induction sends through your body. Without the coil in circuit you will obtain no such shock, though the current stopped when you break the circuit will be many times larger. Break the circuit in gas escaping from a jet; the gas will be ignited. This is the principle of electric gas-lighting systems.

367. The induction coil. The induction coil, as usually made (Fig. 327), consists of a soft iron core C composed of a bundle

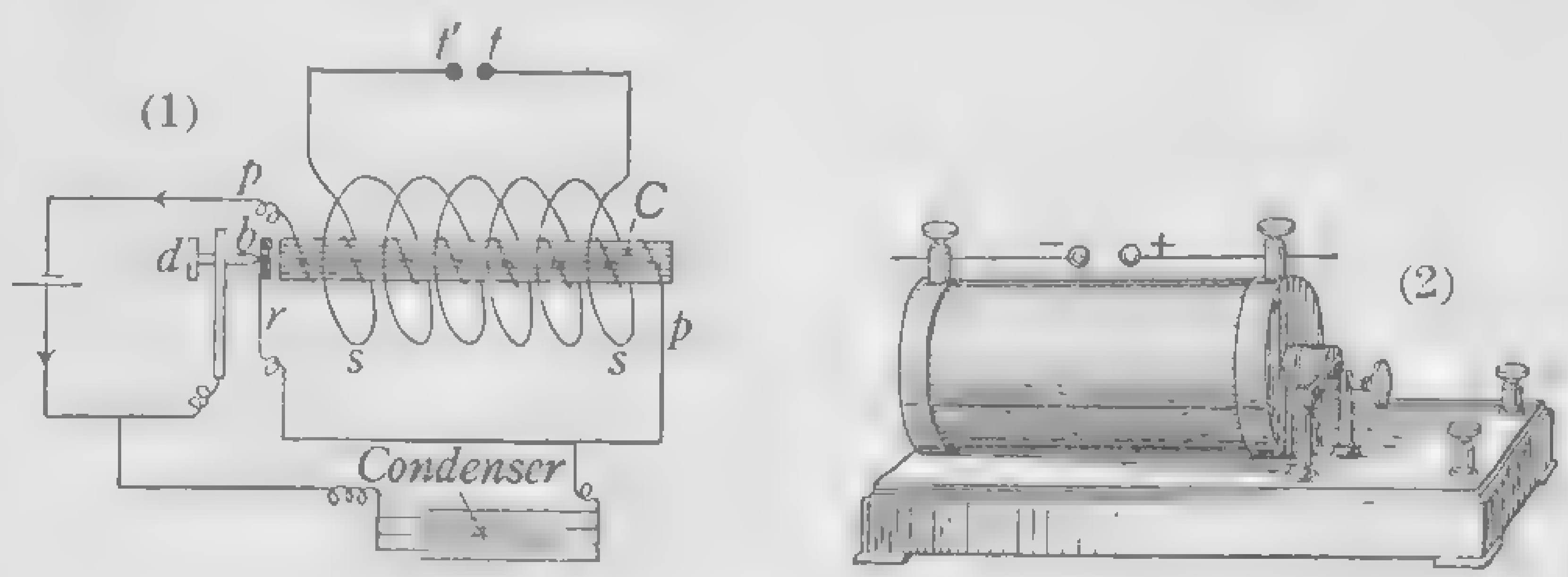


FIG. 327. Induction coil

of soft iron wires; a primary coil p wrapped around this core and consisting of, say, 200 turns of coarse copper wire (for example, No. 16), which is connected into the circuit of a battery through the contact point at the end of the screw d;

a secondary coil s surrounding the primary in the manner indicated in the diagram and consisting generally of between 30,000 and 1,000,000 turns of No. 36 copper wire, the terminals of which are the points t and t'; and a hammer b, or other automatic arrangement for making and breaking the circuit of the primary. (See ignition system opposite page 211.)

Let the hammer b be held away from the opposite contact point by means of the finger, then touched to this point, then pulled quickly away. *A spark will be found to pass between t and t′ at break only — never at make.* This is because, on account of the opposing influence at *make* of self-induction in the primary, the magnetic field about the primary rises very gradually to its full strength, and hence its lines pass into the secondary coil comparatively slowly. At *break*, however, by separating the contact points very quickly we can make the current in the primary fall to zero in an exceedingly short time, perhaps not more than .00001 second; that is, we can make all its lines pass out of the coil in this time. Hence the *rate* at which lines thread through or cut the secondary is perhaps 10,000 times as great at break as at make, and therefore the E.M.F. is also something like 10,000 times as great. In the normal use of the coil the circuit of the primary is automatically made and broken at b by means of the magnet and the spring r, precisely as in the case of the electric bell. Let the student analyze this part of the coil for himself. The condenser shown in the diagram, with its two sets of plates connected to the conductors on either side of the spark gap between r and d, is not an essential part of a coil, but when it is introduced it is found that the length of the spark which can be sent across between t and t' is considerably increased. The reason is as follows: When the circuit is broken at b, the inertia (that is, the self-induction) of the primary current tends to make a spark jump across from d to b; and if this happens, the current continues to flow through this spark (or arc) until the terminals have become separated through a considerable distance. This makes the current die down gradually instead of suddenly, as it ought to do to produce a high E.M.F.; but when a condenser is inserted, as soon as b begins to leave d the current begins to flow into the condenser, and this gives the hammer time to get so far away from d that an arc cannot be formed. This means a sudden break and a high E.M.F. Since a spark passes

between t and t' only at break, it must always pass in the same direction. Coils which give 24-inch sparks (perhaps 500,000 volts) are not uncommon. Such coils usually have hundreds of miles of wire upon their secondaries.

368. Laminated cores; Foucault currents. The core of an induction coil should always be made of a bundle of soft-iron wires insulated from one another by means of shellac or varnish (see Fig. 328); for whenever a current is started or stopped in the primary p of a coil furnished with a *solid* iron core (see Fig. 329), the change in the magnetic field of the primary induces a current in the conducting core C, for the same reason that it induces one in the secondary s. This current flows around the body of the core in the same direction as the induced current in the secondary, that is, in the direction of the arrows. The only effect of these so-called *eddy* or *Foucault* currents is to heat the core. This is obviously a waste of energy. If we can prevent the appearance of these currents, all the energy which they would waste in heating the core may be made to appear in the current of the secondary. The core is therefore built of varnished iron wires, which run parallel to the axis of the coil, that is to say, perpendicular to the direction in which the currents would be induced. The induced E.M.F. therefore finds no closed circuits in which to set up a current (Fig. 328). It is for the same reason that the iron cores of dynamo and motor armatures, instead of being solid, consist of iron disks placed side by side, as shown in Fig. 330, and insulated from one another by films of oxide. A core of this kind is called a *laminated* core. It will be seen that in all such cores the spaces or slots between the laminæ must run *at right angles to the direction of the induced E.M.F.*, that is, perpendicular to the conductors upon the core.

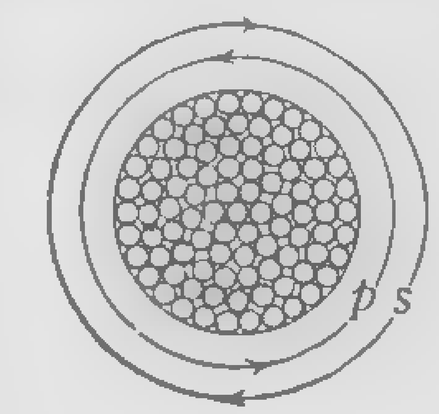


FIG. 328. Core of insulated iron wire

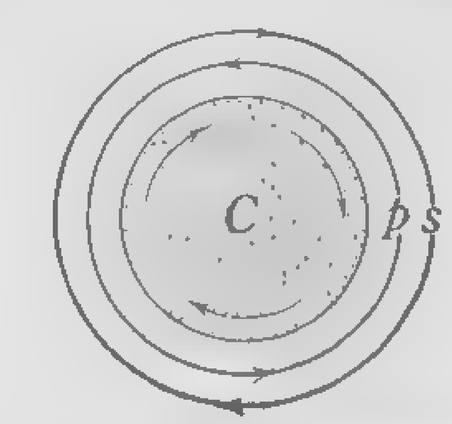


FIG. 329. Diagram showing eddy currents in solid core

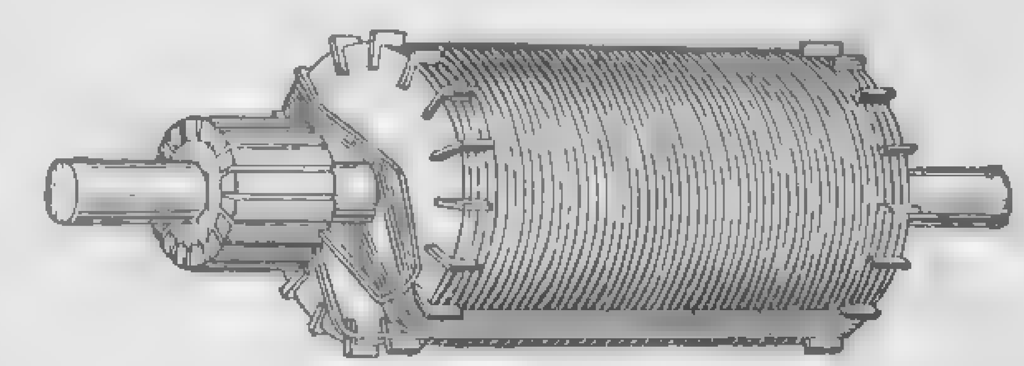


FIG. 330. Laminated drum-armature core with commutator, showing one coil wound on the core

369. The transformer. The chief difference between an induction coil and a transformer is that in the latter the core R (Fig. 331), instead of being straight, is bent into the form of a ring or is given some other shape such that the magnetic lines of force have a continuous iron path instead of being obliged to push out into the air, as in the induction coil. Furthermore, it is always an alternating instead of an intermittent current which is sent through the primary A. Sending such a current through A is equivalent to first magnetizing the core in one direction, then demagnetizing it, then magnetizing it in the opposite direction, etc. The result of these changes in the magnetism of the core is of course an induced alternating current within the secondary coil B.

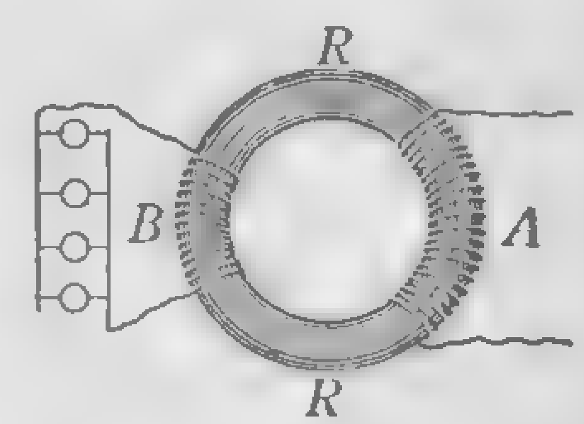


FIG. 331. Diagram of transformer

370. The use of the transformer. The use of the transformer is to convert an alternating current from one voltage to another which, for some reason, is found to be more convenient. In electric lighting, for example, where an alternating current is used, the E.M.F. generated by the dynamo is usually either 1100 or 2200 volts, a voltage too high to be introduced safely into private houses. Hence transformers are connected across the main conductors in the manner shown in Fig. 332. The current which passes into the houses to supply the lamps does not come directly from the dynamo. It is an induced current generated in the transformer.

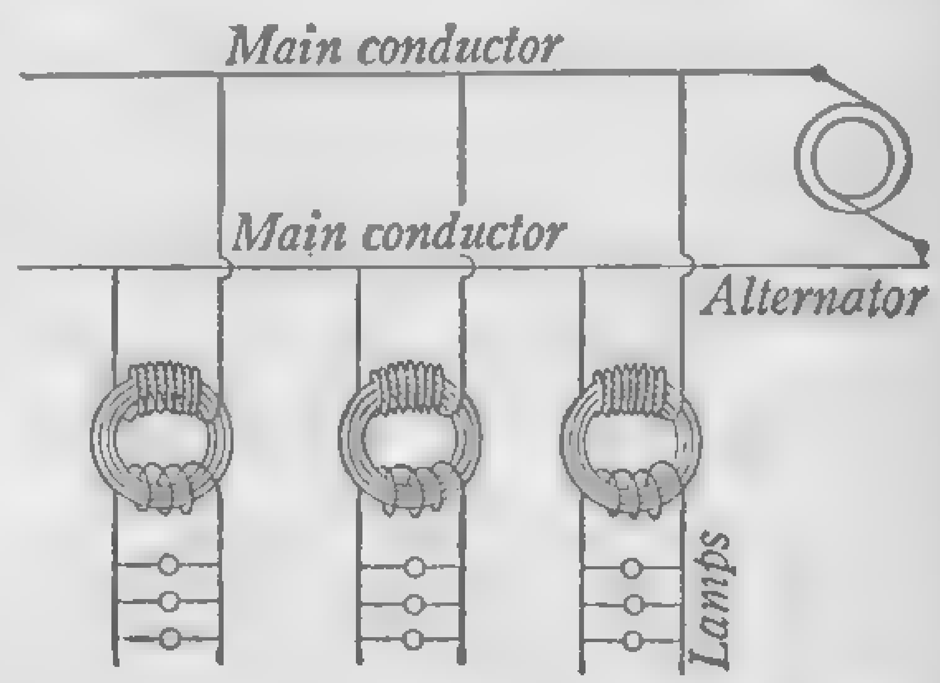


FIG. 332. Alternating-current lighting circuit with transformers

Through the use of small transformers the voltage of the current of the house lighting circuit is further reduced and made available for the ringing of doorbells.

371. Pressure in primary and secondary. If there are a few turns in the primary and a large number in the secondary, the transformer is called a *step-up* transformer, because the P.D. produced at the terminals of the secondary is greater than that applied at the terminals of the primary. In electric lighting, transformers are mostly of the *step-down* type; that is, a high P.D. (say, 2200 volts) is applied at the terminal of the primary, and a lower P.D. (say, 110 volts) is obtained at the terminals of the secondary. In such a transformer the primary will have twenty times as many turns as the secondary. In general, *the ratio between the voltages at the terminals of the primary and secondary is the ratio of the number of turns of wire upon the two.*

372. Efficiency of the transformer. In a perfect transformer the efficiency would be unity. This means that the electric power, or watts, put into the primary (that is, the volts applied to its terminals times the amperes flowing through it) would be exactly equal to the power, or watts, taken out in the secondary (that is, the volts generated in it times the strength of the induced current); and, in fact, in actual transformers the latter product is often more than 97 per cent of the former (that is, there is less than 3 per cent loss of energy in the transformation). This lost energy appears as heat in the transformer. This transfer which goes on in a big transformer of huge quantities of power from one circuit to another entirely independent circuit, without noise or motion of any sort and almost without loss, is one of the most wonderful phenomena of modern industrial life.

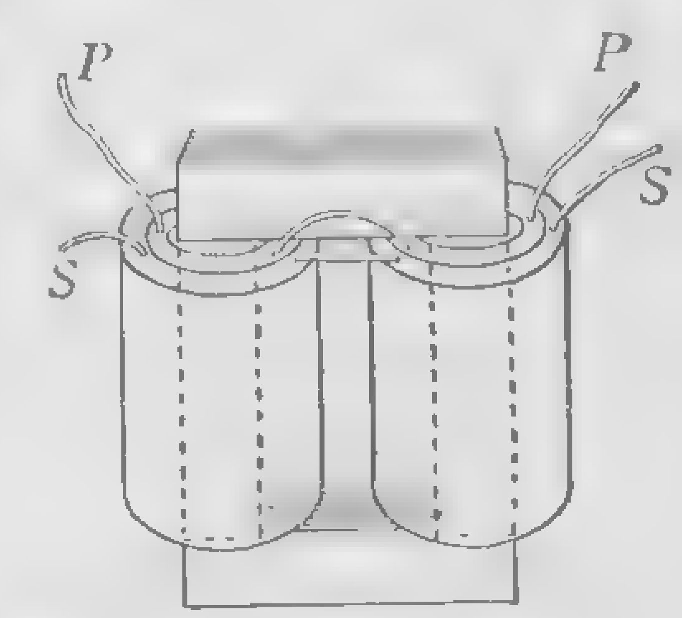


FIG. 333. The core type of transformer

373. Commercial transformers. Fig. 333 illustrates a common type of transformer used in electric lighting. The core is built up of sheet-iron laminæ about $\frac{1}{2}$ millimeter thick. Fig. 334 shows a section of the same transformer. The closed magnetic circuit of the core is indicated by the dotted

lines. The primaries and the secondaries are indicated by the letters P and S. Fig. 335 is the case in which the transformer is placed. Such cases may be seen attached to poles outside houses wherever alternating currents are used for electric lighting (Fig. 336).

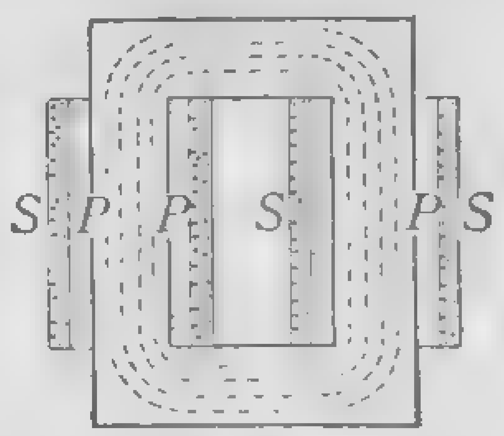


FIG. 334. Cross-section of transformer, showing shape of magnetic field

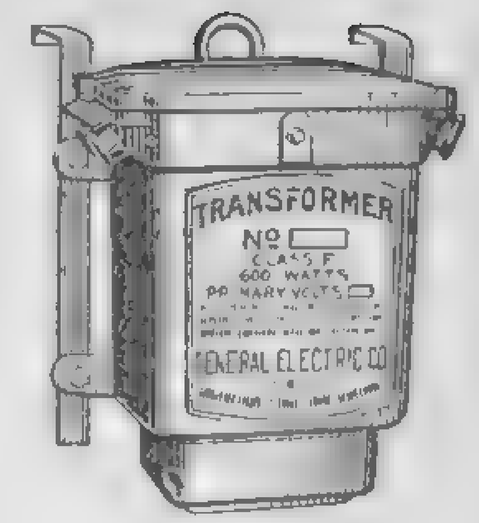


FIG. 335. Transformer case

374. Electrical transmission of power. Since the rate of production of electric energy by a dynamo is the product of the E.M.F. generated by the current furnished, it is evident that in order to transmit from one point to another a given number of watts, say, 10,000, it is possible to have either an E.M.F. of 100 volts and a current of 100 amperes or an E.M.F. of 1000 volts and a current of 10 amperes. In the two cases, however, the loss of energy in the wire which carries the current from the place where it is generated to the place where it is used will be widely different. For,

Watts = amperes × volts;

but, from Ohm's law,

Volts = amperes × ohms.

Therefore

Watts = amperes² × ohms = I^2R.

If, then, R represents the resistance of this transmitting wire, the so-called *line resistance*, and I the current flowing through it, the heat developed in it will be proportional to I^2R. Hence the energy wasted in heating the line will be but $\frac{1}{100}$ as much in the case of the 1000-volt, 10-ampere current as in the case of the 100-volt, 100-ampere current. Hence for long-distance transmission, where line losses are considerable, it is important to use the highest possible voltages.

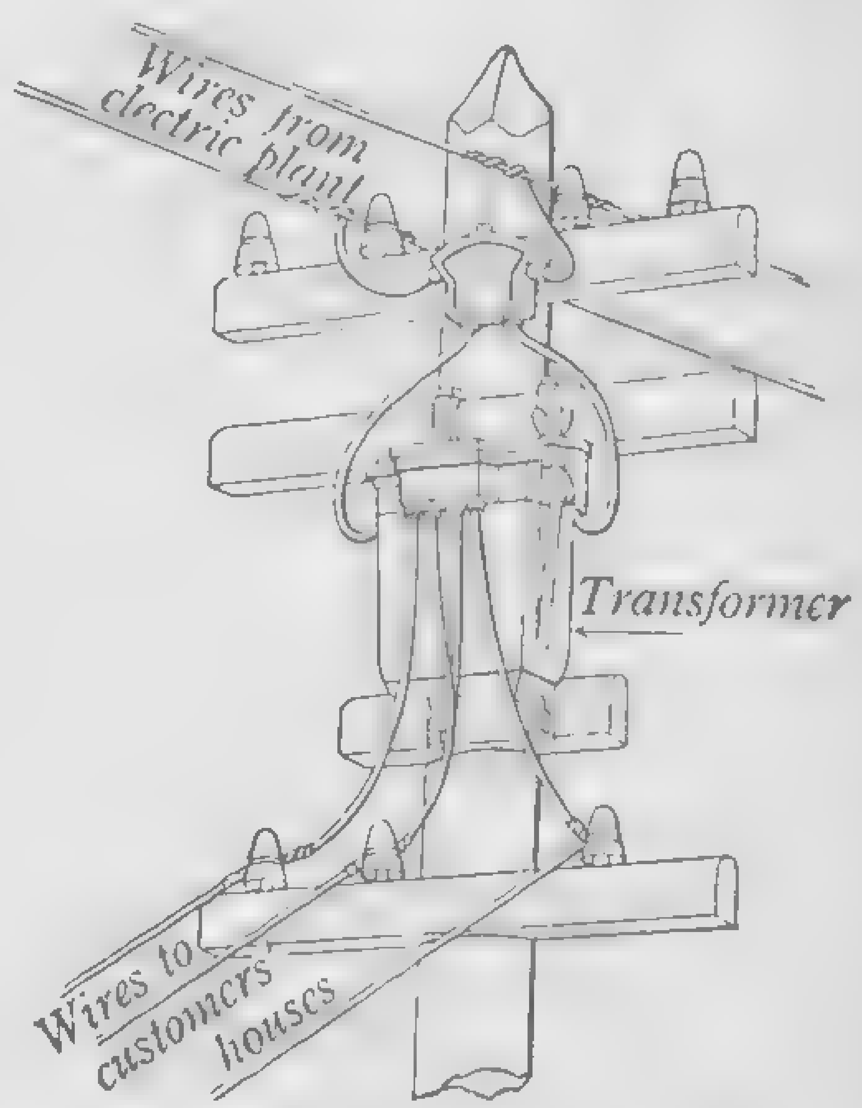


FIG. 336. Transformer on electric-light pole

On account of the difficulty of insulating the commutator segments from one another, voltages higher than 1200 or 1500 cannot be obtained with direct-current dynamos of the kind that have been described. With alternators, however, the difficulties of insulation are very much less on account of the absence of a commutator. The large 87,000-horse-power alternating-current dynamos on the American side of Niagara Falls generate directly 12,000 volts. This is the highest voltage thus far produced by generators. In all cases where these high pressures are employed they are transformed down at the receiving end of the line to a safe and convenient voltage (from 50 to 500 volts) by means of *step-down* transformers.

It will be seen from the facts given above that alternating currents are best suited for long-distance transmission. The Big Creek

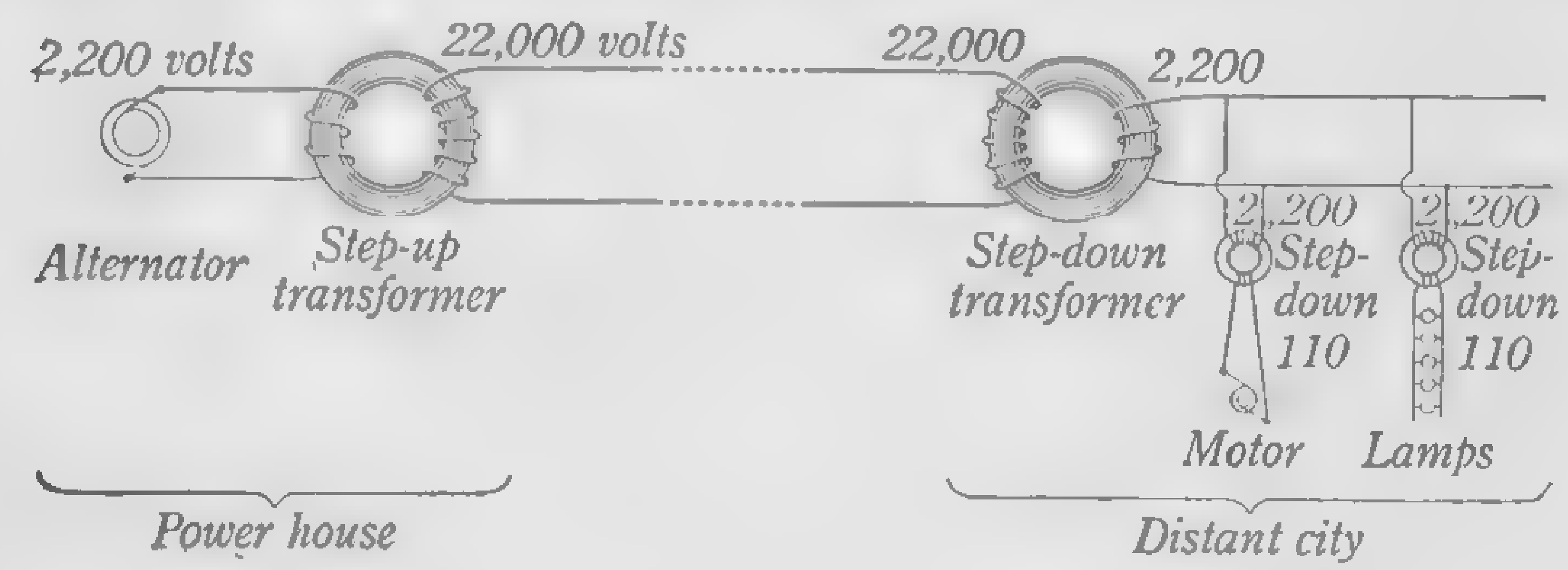


FIG. 337. High-voltage long-distance transmission line

plant in California transmits power 241 miles at a pressure of 220,000 volts. (See opposite page 145.) The Southern Sierras Power Company sends current 830 miles across the desert. In all such cases *step-up* transformers, situated at the power house, transfer the electrical energy developed by the generator to the line, and *step-down* transformers, situated at the receiving end, transfer it to the motors or lamps which are to be supplied (Fig. 337). (See opposite pages 144 and 276 for hydroelectric plants in which dynamos are run by water wheels.)

375. The tungar rectifier. Negative electrons are found to escape from a filament that is heated to incandescence; and if this filament is then made more than, say, 25 volts negative with respect to a neighboring anode, any gas that surrounds the filament is found to be ionized (split into positively and negatively charged parts) by the violence of the blows which the electrons strike

against its molecules. It is thus rendered conducting. These facts are utilized in the tungar rectifier of the alternating current. The bulb (Fig. 338) is filled with argon to a pressure of 3 to 8 cm. The anode is a small cone of graphite or tungsten, and the cathode is a coiled tungsten filament. When the rectifier is in operation, the cone and the filament are alternately + and −, one being + while the other is −. When the cone is + and the filament −, the negative electrons from the filament are forced across the space from the filament to the cone, and the argon, which is thereby ionized, carries the current from the cone to the filament. When the cone is − and the filament +, the negative electrons cannot escape from the filament; hence the gas does not become conducting. The principle of operation can be understood from Fig. 339.

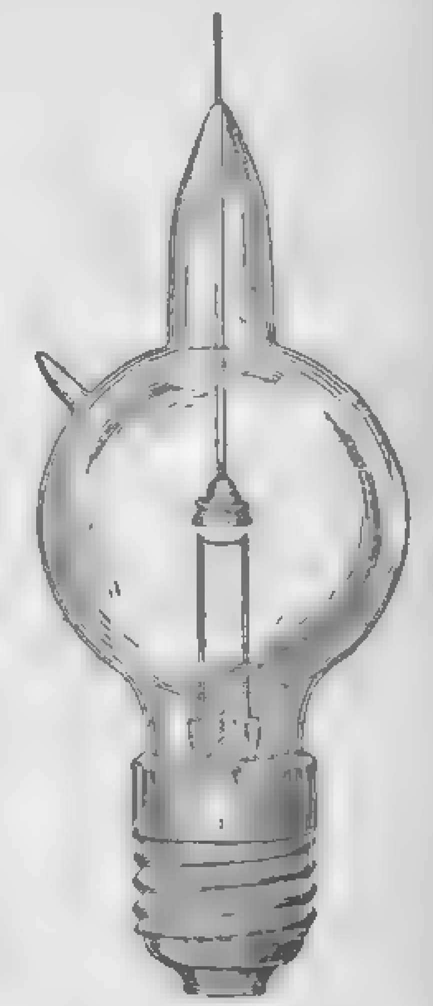


FIG. 338. Tungar bulb

The rectifier is connected to the alternating-current line at C and D. The alternating current in the primary coil P of the transformer T causes an induced current in S, which keeps the filament F incandescent. Under the action of the current, A and F are alternately + and −. When F is −, the electrons escape and ionize the gas, permitting the current to pass. When F is + the negative electrons are driven back into the filament and cannot escape to ionize the gas. Hence no current passes. In this way a unidirectional pulsating current passes through the storage batteries or other load. This rectifier is used largely in charging storage batteries for small-power purposes and for radio receiving sets. Rectifying bulbs are frequently used in parallel to obtain greater charging power.

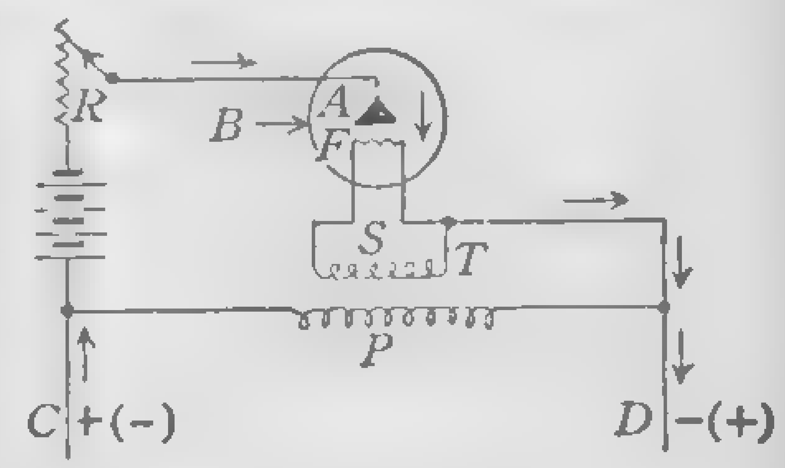


FIG. 339. Principle of operation of the tungar rectifier

376. Principle of the carbon microphone. Let a dry cell, an ammeter, and two pieces of electric-arc carbon be arranged in series (Fig. 340). Press the carbons *very gently* and observe the reading of the ammeter. Press gradually harder, then gradually less, watching the instrument. The current increases with increase in pressure, and decreases with decrease in pressure.

This peculiar behavior of carbon in offering a variable resistance with variation in pressure is taken advantage of in constructing the carbon transmitter of the telephone. In the modern transmitter, however, the current is made to traverse many particles of granular carbon, which, lying loosely together, furnish a very great number of loose contacts (see Fig. 343).

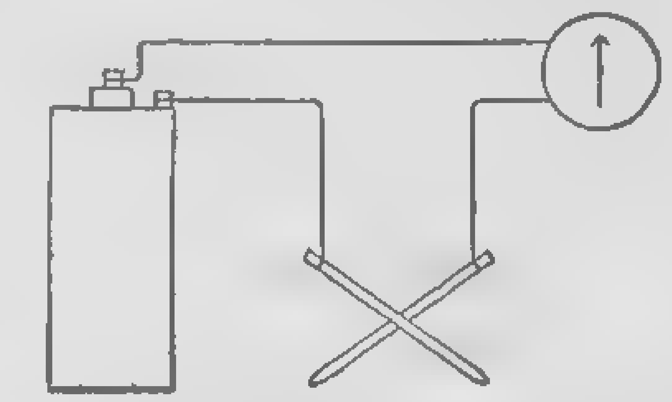


FIG. 340. The principle of the carbon transmitter

377. Principle of the telephone. The telephone was invented in 1875 by Alexander Graham Bell of Washington (see opposite page 428) and Elisha Gray of Chicago. The simple local-battery system is shown in Fig. 341.

The current from the battery B (Fig. 341) is led first to the back of the diaphragm E, whence it passes through a little chamber C, filled with granular carbon, to the conducting back d of the transmitter, and thence through the primary coil p of the transformer, and then back to the battery B.

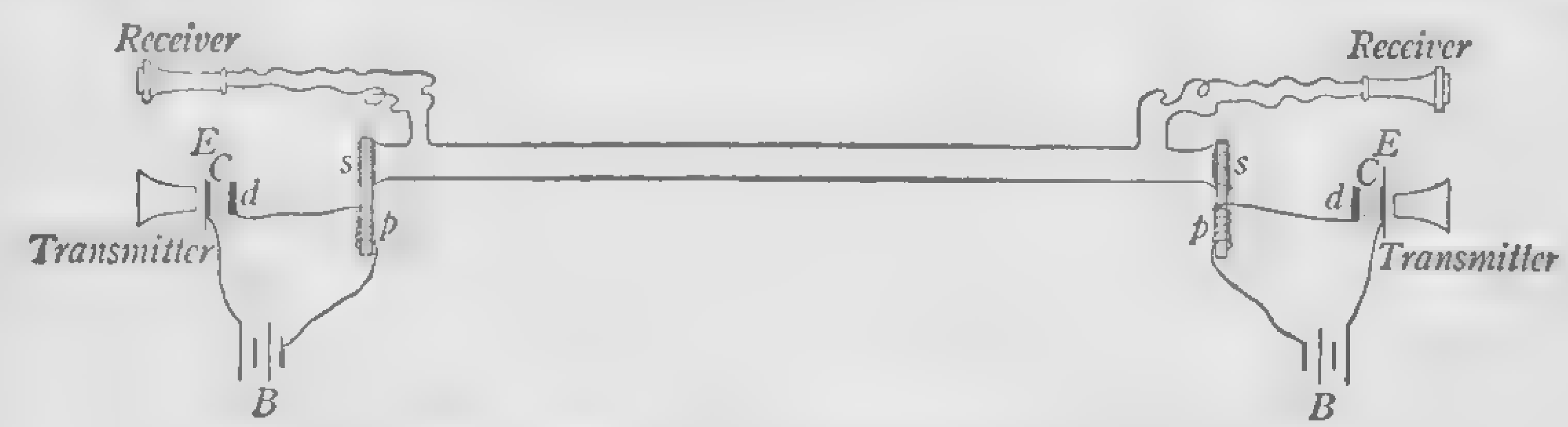


FIG. 341. The telephone circuit (local-battery system)

When a sound is made in front of the microphone, the vibrations produced by the sounding body are transmitted by the air to the diaphragm, thus causing the latter to vibrate back and forth. These vibrations of the diaphragm vary the pressure upon the many contact points of the granular carbon through which the primary current flows. This produces considerable variation in the resistance of the primary circuit, so that as the diaphragm moves forward, that is, toward the car-

bon, a comparatively large current flows through p, and as it moves back, a much smaller current. These changes in the current strength in the primary p produce changes in the magnetic field of the soft-iron core of the transformer. Currents are therefore induced in the secondary s of the transformer and these currents pass over the line and affect the receiver at the other end. A step-up transformer is used to get sufficient potential to work through the high resistance of a long line.

A modern telephone receiver is shown in Fig. 342. It consists of a permanently magnetized U-shaped piece of steel in front of whose poles is a soft-iron diaphragm which *almost* touches the ends of the magnet. Wound in opposite directions upon the two poles are coils of fine insulated wire in series with each other and the line wire. G is the earpiece, E the diaphragm, A the U-shaped magnet, and B the coils, consisting of many turns of fine wire and having soft-iron cores. When the rapidly alternating current from the secondary coil s (Fig. 341) flows through the coils of the receiver, the poles of the permanent magnet are thereby alternately strengthened and weakened in synchronism with the sound waves falling upon the diaphragm of the transmitter. The variations in the magnetic pull upon the diaphragm of the receiver cause it to send out sound waves exactly like those which fell upon the diaphragm of the transmitter.

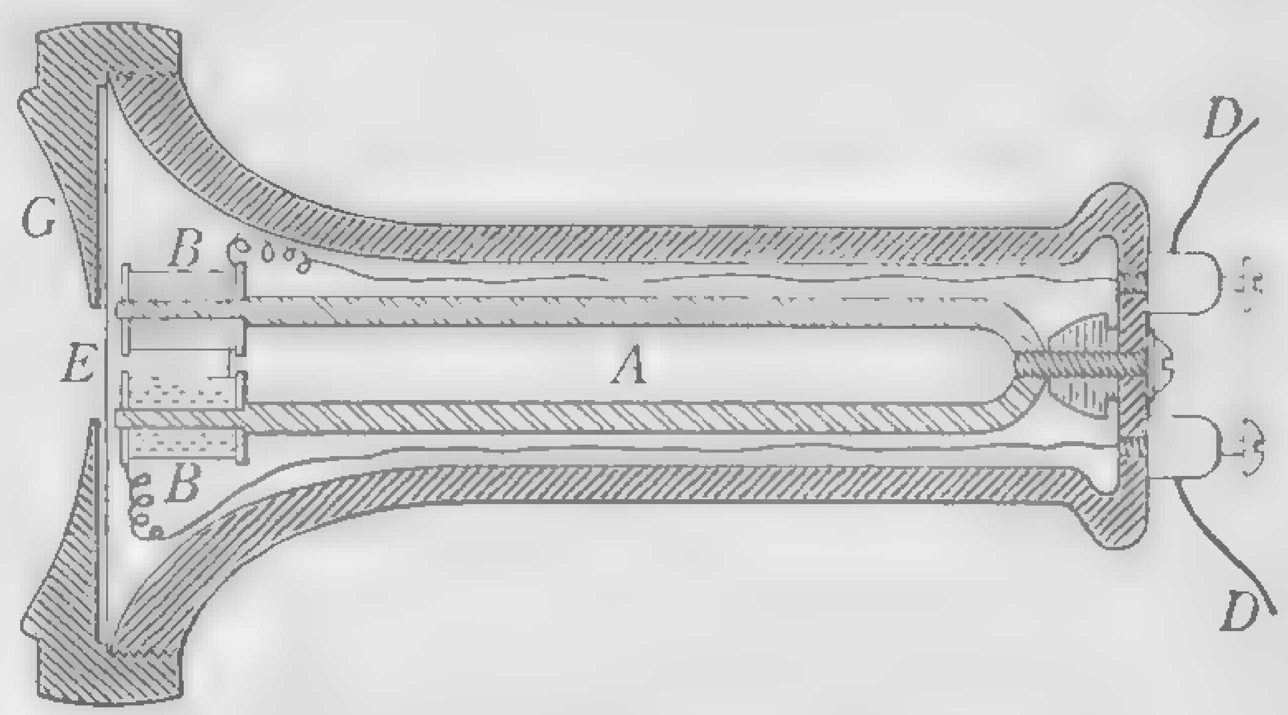


FIG. 342. The modern receiver

Telephonic conversation can be carried on over great distances as rapidly as if the parties sat on opposite sides of the same table. An electrical impulse passes over the telephone

wires from New York to San Francisco in about one fifteenth of a second. The use of distortionless vacuum-tube repeaters makes possible such long-distance transmission of speech. There are 15,000,000 telephones in use in the United States and 25,000,000 miles of telephone wire. The New York-Chicago telephone cable, constructed at a cost of $25,000,000, is 861 miles long, $2\frac{5}{8}$ inches in diameter, and contains 447,000 miles of wire. It can carry 250 telephone messages and, simultaneously with them, 500 telegraph messages. The cross section of a complete long-distance transmitter is shown in Fig. 343. The current traverses granular carbon held between solid blocks of carbon.

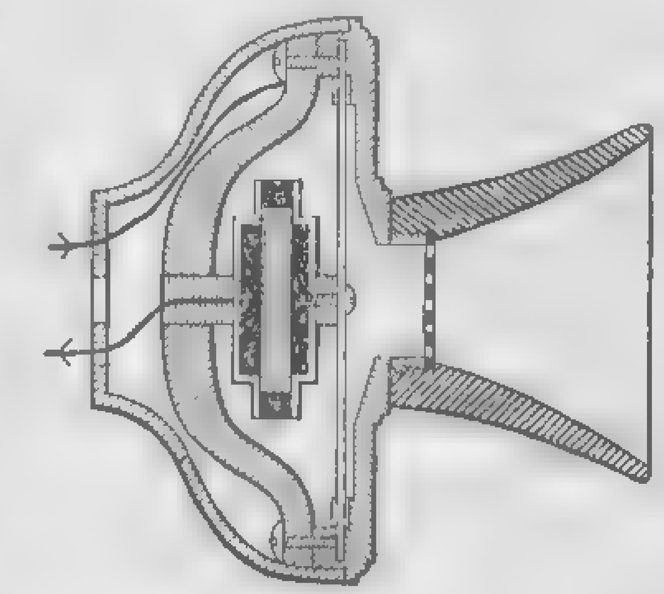


FIG. 343. Cross section of a long-distance telephone transmitter

SUMMARY. While the primary current is increasing, the induced current in the secondary flows opposite to it. While the primary current is decreasing, the induced current flows in the same direction.

Self-induction is the occurrence of an induced E.M.F. in a part of the same circuit in which the original current flows, and, in accord with Lenz's law, it makes the current appear to have inertia.

Laminated cores are used in transformers and in the armatures of dynamos and motors to prevent the development of the heat-producing Foucault currents.

The ratio of the voltages in the primary and secondary coils of a transformer is equal to the ratio of their respective number of turns.

In long-distance transmission, heat losses in the line are minimized by using high voltage and low amperage.

Vacuum-tube rectifiers depend for their action upon electron emission by incandescent bodies.

The microphone depends for its action upon the variable resistance of carbon under changing pressure.

In a telephone receiver the poles of a permanent magnet are alternately strengthened and weakened, but not reversed in polarity.

QUESTIONS AND PROBLEMS *

1. Draw a diagram of an induction coil and explain its action.

2. Explain why an induction coil is able to produce such an enormous E.M.F.

3. Represent by a diagram a step-up transformer and label the essential parts.

4. What relation must exist between the number of turns on the primary and secondary of a transformer which feeds 110-volt lamps from a main line whose conductors are at 1100 volts P.D.?

5. Make a diagram to show how in the electric doorbell transformer the 104-volt house current is transformed to an 8-volt current to ring the bell.

6. A transformer is desired to step down from 220 to 6 volts, and is wound with 1100 turns in the primary coil. How many turns should be put in the secondary coil?

7. Suppose 5,000,000 watts of electric power are to be transmitted a great distance. Which is the more economical way to transmit it, as 50 amperes at 100,000 volts or as 5000 amperes at 1000 volts? Give reason for your answer.

8. A current of 3 amperes at 1000 volts is sent through the primary coil of a transformer having an efficiency of 97 per cent. How many 40-watt lamps can be lighted when connected to the secondary coil of the transformer?

9. Why does a tungar rectifier rectify an alternating current?

10. In telephoning from New York to San Francisco how far do you think the sound goes? What passes along the telephone wire?

11. Diagram a simple telephone similar to Fig. 341 in which are shown only those parts that are necessary to enable one party to speak to the other, no reply from the second party being possible.

12. Make from memory a careful sketch of a telephone transmitter and a receiver, including battery and connections, and explain the action of each instrument.

13. Name three modern electrical instruments or machines which have resulted from Oersted's discovery and three that have resulted from Faraday's.

* Supplementary questions and problems for Chapter XV are given in the Appendix.

CHAPTER XVI *

NATURE AND TRANSMISSION OF SOUND

SPEED AND NATURE OF SOUND

378. Sources of sound. If a sounding tuning fork provided with a stylus is stroked across a smoked-glass plate, it produces a wavy line, as shown in Fig. 344; if a light suspended ball is brought into contact with it, the latter is thrown off with considerable violence. If we look about for the source of any sudden noise, we find that

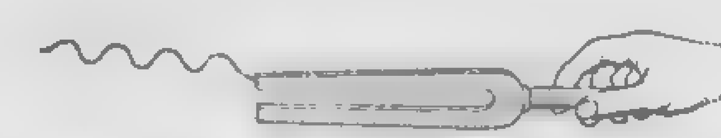


FIG. 344. Trace made by vibrating fork

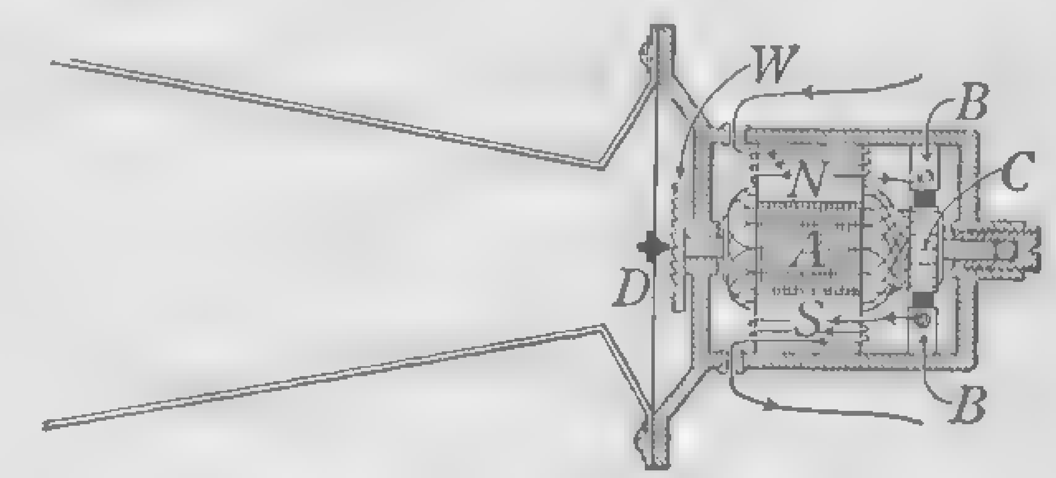


FIG. 345. A motor-type automobile horn

some object has fallen, or some collision has occurred, or some explosion has taken place, — in a word, that some violent motion of matter has been set up in some way. Fig. 345 shows how this is accomplished in the case of a motor-type automobile horn. From these familiar facts we conclude that *sound arises from the motions of matter.*

379. Media of transmission. Air is ordinarily the medium through which sound comes to our ears, yet an Indian puts his ear to the ground to hear a distant noise, and most boys know how loud the clapping of stones sounds under water. If a very long rod is pressed against a blackboard, and the

* This chapter should be accompanied by laboratory experiments on the speed of sound in air, the vibration rate of a fork, and the determination of wave lengths. See, for example, Experiments 50, 51, and 52 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

stem of a vibrating tuning fork pressed against the outer end, a loud sound will come from the blackboard. If the base of the sounding fork of Fig. 344, fitted to a piece of wood, is held in a dish of water, the sound will be markedly transmitted by the water to a resonance box (Fig. 346). These facts show that a gas like air is certainly no more effective in the transmission of sound than a liquid or a solid. Next let us see whether or not matter is necessary at all for the transmission of sound.

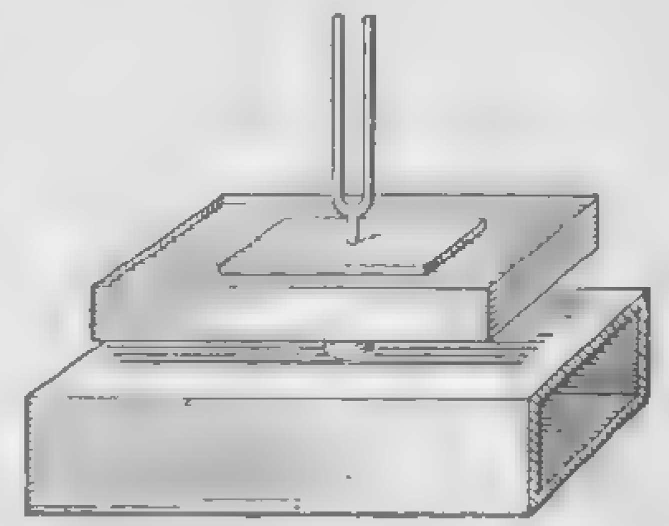


FIG. 346. Transmission of sound through water

Let an electric bell be suspended inside the receiver of an air pump by means of two fine springs which pass through a rubber stopper in the manner shown in Fig. 347. Let the air be exhausted from the receiver by means of the pump. The sound of the bell will be found to become less and less pronounced. Let the air be suddenly readmitted. The volume of sound will at once increase.

Since, the nearer we approach a vacuum, the less distinct becomes the sound, we infer that sound cannot be transferred through a vacuum and that therefore *the transmission of sound is effected only through the agency of ordinary matter.* In this respect sound differs from heat and light, which evidently pass with perfect readiness through a vacuum, since they reach the earth from the sun and stars.

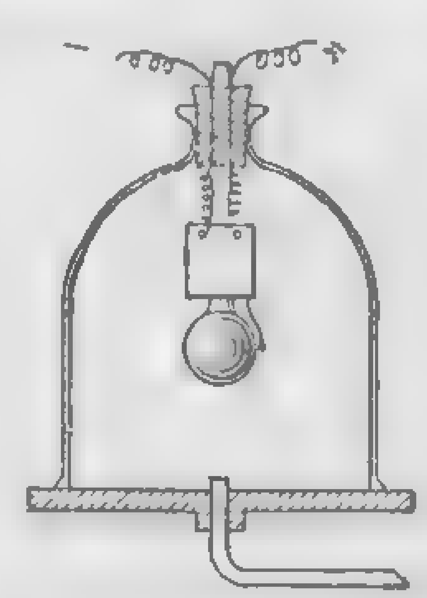


FIG. 347. Sound not transmitted through a vacuum

380. Speed of transmission. The first attempt to measure accurately the speed of sound was made in 1738, when a commission of the French Academy of Sciences stationed two parties about three miles apart and observed the interval between the flash of a cannon and the sound of the report. By taking observations between the two stations, first in one direction and then in the other, the effect of the

wind was eliminated. A second commission repeated these experiments in 1832, using a distance of 18.6 kilometers, or a little more than 11.5 miles. The value found was 331.2 meters per second at 0° C. The accepted value is now 331.3 meters. The speed in water is about 1400 meters per second, and in iron 5100 meters.

The speed of sound in air is found to increase with an increase in temperature. The amount of this increase is about 60 centimeters per second per degree centigrade, or about 2 feet per second per degree centigrade. Hence the speed at 20° C. is about 343.3 meters per second. It is sufficiently accurate to remember 1090 feet per second at 0° C. (= 32° F.), or 1130 feet per second at 20° C. (= 68° F.).

381. Mechanism of transmission. When a firecracker or toy cap explodes, the powder is suddenly changed to a gas, the volume of which is enormously greater than the volume of the powder. The air is therefore suddenly pushed back in all directions from the center of the explosion. This means that the air particles which lie about this center are given violent outward velocities.* When these outwardly impelled air particles collide with other particles, they give up their outward motion to these second particles, and these in turn pass it on to others, etc. It is clear, therefore, that the motion started by the explosion must travel on from particle to particle to an indefinite distance from the center of the explosion. (See opposite pages 362 and 419.) Furthermore, it is also clear that, although the motion travels on to great distances, the individual particles do not move far from their original positions; for it is easy to show experimentally that whenever an elastic body in motion collides with another similar body at rest, the colliding body simply transfers its motion to the body at rest and comes itself to rest.

* These outward velocities are simply superposed upon the velocities of agitation which the molecules already have on account of their temperature. For our present purpose we may ignore entirely the existence of these latter velocities and treat the particles as though they were at rest, save for the velocities imparted by the explosion.

Let six or eight equal steel balls be hung from cords in the manner shown in Fig. 348. First let all the balls but two adjacent ones be held to one side, and let one of these two be raised and allowed to fall against the other. The first ball will be found to lose its motion in the collision, and the second will be found to rise to practically the same height as that from which the first fell. Next let all the balls be placed in line and the end one raised and allowed to fall as before. The motion will be transmitted from ball to ball, each giving up the whole of its motion practically as soon as it receives it, and the last ball will move on alone with the velocity which the first ball originally had.

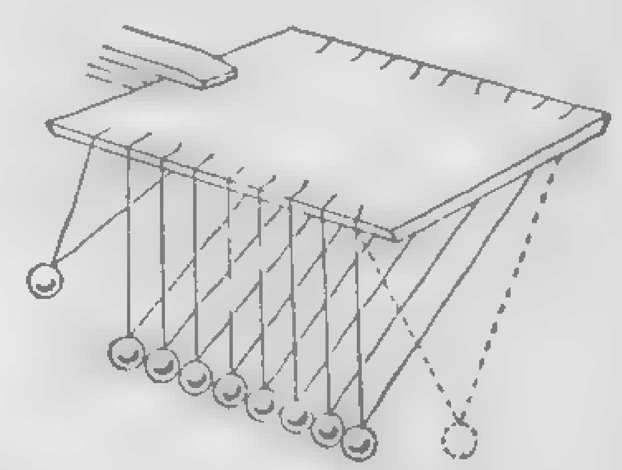


FIG. 348. Illustrating the propagation of sound from particle to particle

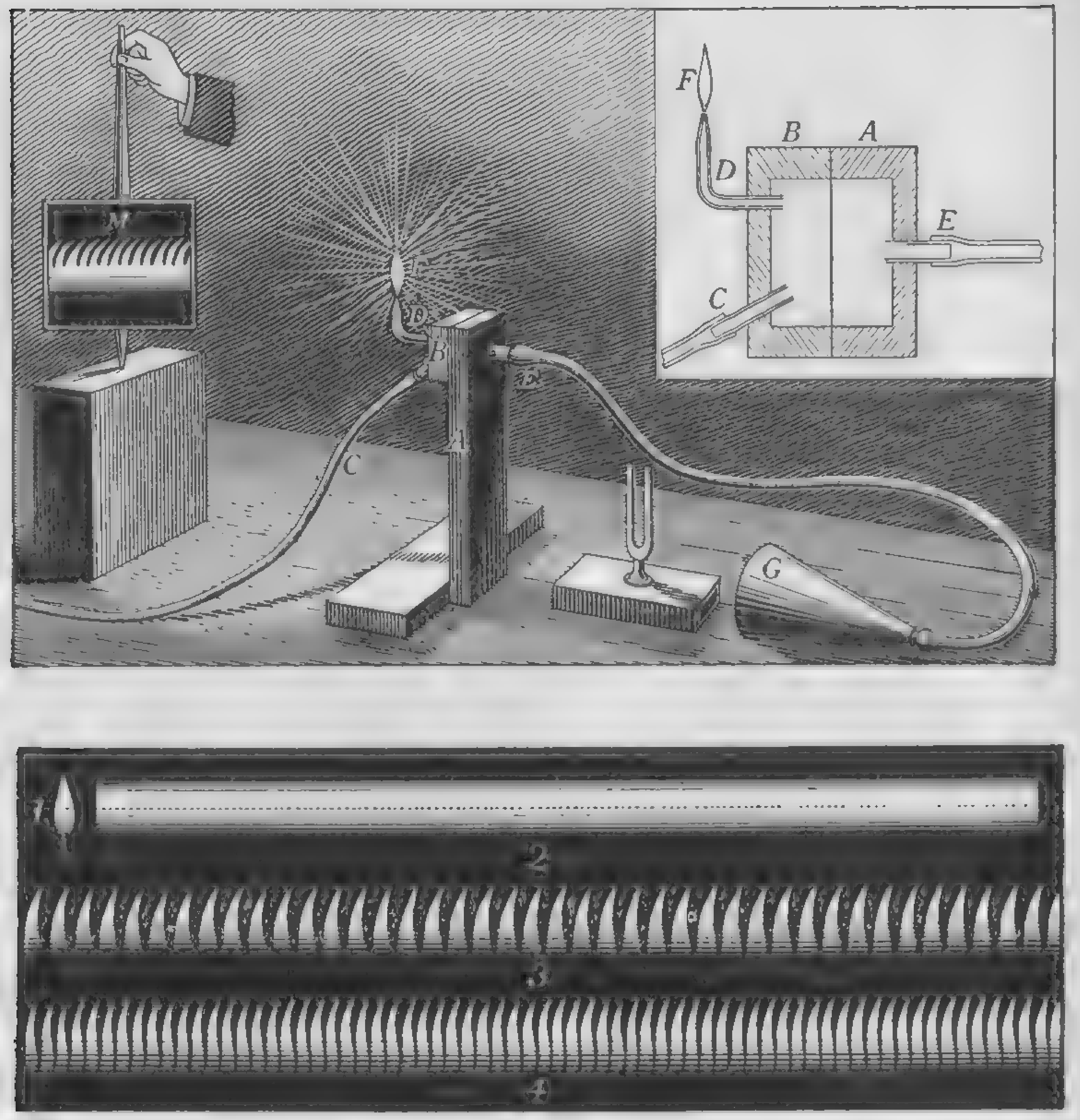
The preceding experiment furnishes a very nice mechanical illustration of the manner in which the air particles which receive motions from an exploding firecracker or a vibrating tuning fork transmit these motions in all directions to neighboring layers of air, these in turn to the next adjoining layers, etc., until the motion has traveled to very great distances, although the individual particles themselves move only very minute distances. When a motion of this sort, transmitted by air particles, reaches the drum of the ear, it produces the sensation which we call *sound*. In physics, however, the word "sound" means not the sensation but rather the wave motion capable of producing it.

382. A train of waves ; wave length. In the preceding paragraphs we have confined attention to a single pulse traveling out from a center of explosion. A very simple and beautiful way of showing the sort of disturbance which is set up in the air by a continuously vibrating body is furnished by the so-called *manometric flames* (see opposite page 349).

First let the mirror be rotated when no note is sounded before the mouthpiece. There will be no fluctuations in the flame, and its image, as seen in the moving mirror, will be a straight band, as shown in 2. Next let a mounted *C* fork be sounded, or some other

HERMANN LUDWIG FERDINAND VON HELMHOLTZ (1821–1894)

Noted German physicist and physiologist; professor of physiology and anatomy at Bonn and at Heidelberg from 1855 to 1871; professor of physics at Berlin from 1871 to 1894; published in 1847 a famous paper on the conservation of energy, which was most influential in establishing that doctrine; invented the ophthalmoscope; discovered the physical significance of tone quality and made other contributions to acoustics and optics; was preëminent also as a mathematical physicist



MANOMETRIC FLAMES

This device consists of the following parts: a chamber in the block B, through which gas is led by way of the tubes C and D to the flame F; a second chamber in the block A, separated from the first chamber by an elastic diaphragm made of very thin sheet rubber or paper and communicating with the source of sound through the tube E and trumpet G; and a rotating mirror M by which the flame is observed. With constant speed of rotation the number of teeth per inch gives the pitch of the sound. Quality is also analyzed by the manometric flame, as shown on page 373

simple tone produced in front of G. The image in the mirror will be that shown in 3. Then let another fork having twice as many vibrations per second be sounded in place of the C. The image will be that shown in 4. The images of the flame are now twice as close together as before, since the blows strike the diaphragm twice as often.*

When the note was produced before the mouthpiece G, the up-and-down motions of the flame observed in the revolving mirror were due to variations in the pressure of the gas coming to the flame through the chamber B. These variations in pressure were the direct result of vibrations of the diaphragm which could have been caused in no other way than by a regular succession of air pulses striking upon it.

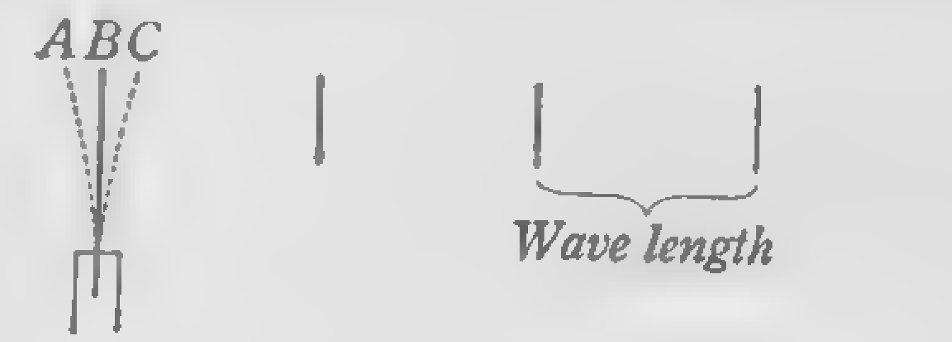


FIG. 349. Vibrating reed sending out a train of equidistant pulses

Consider the pulses produced by the prong of Fig. 349. Each time that this prong moves to the right it sends out a pulse which travels through the air at the rate of 1100 feet per second, in exactly the manner described in the preceding paragraphs. Hence, if the prong is vibrating uniformly, we shall have a continuous succession of pulses following each other through the air at exactly equal intervals. Suppose, for example, that the prong makes 110 complete vibrations per second. Then at the end of one second the first pulse sent out will have reached a distance of 1100 feet. Between this point and the prong there will be 110 pulses distributed at equal intervals; that is, each two adjacent pulses will be just 10 feet apart. If the prong made 220 vibrations per second, the distance between adjacent pulses would be 5 feet, etc. *The distance between two adjacent pulses in such a train of waves is called a wave length.*

* If a rotating mirror is not to be had, a piece of ordinary mirror glass held in the hand and oscillated back and forth about a vertical axis will be found to give satisfactory results.

383. Relation between velocity, wave length, and number of vibrations per second. If n represents the number of vibrations per second of a source of sound, l the wave length, and v the velocity with which the sound travels through the medium, it is evident from the example of the preceding paragraph that the following relation exists between these three quantities:

$$l = \frac{v}{n}, \text{ or } v = nl; \tag{1}$$

that is, *wave length is equal to velocity divided by the number of vibrations per second, or velocity is equal to the number of vibrations per second multiplied by the wave length.*

384. Condensations and rarefactions. Thus far, for the sake of simplicity, we have considered a train of waves as a series of thin, detached pulses separated by equal intervals of air at

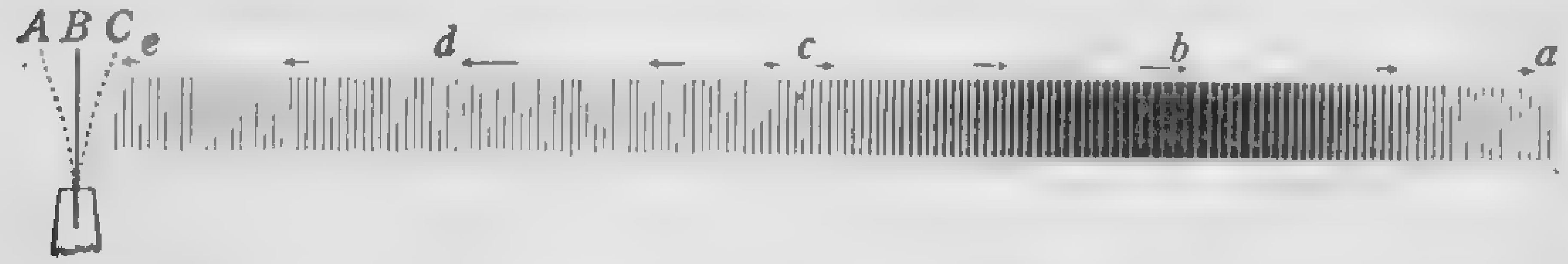


FIG. 350. Illustrating motions of air particles in one complete sound wave consisting of a condensation and a rarefaction

rest. In point of fact, however, the air in front of the prong B (Fig. 349) is being pushed forward not at one particular instant only but during all the time that the prong is moving from A to C, that is, through the time of one-half vibration of the fork; and during all this time this forward motion is being transmitted to layers of air which are farther and farther away from the prong, so that when the latter reaches C, all the air between C and some point c (Fig. 350) one-half wave length away is crowding forward and is therefore in a state of compression, or *condensation*. Again, as the prong moves back from C to A, since it tends to leave a vacuum behind it, the adjoining layer of air rushes in to fill up this space, the layer next adjoining follows, etc., so that when the prong reaches A, all the air between A and c (Fig. 350) is moving

backward and is therefore in a state of diminished density, or *rarefaction*. During this time the preceding forward motion has advanced one half wave length to the right, so that it now occupies the region between c and a (Fig. 350). Hence at the end of one complete vibration of the prong we may divide the air between it and a point one wave length away into two portions, one a region of condensation ac, and the other a region of rarefaction ce. The arrows in Fig. 350 represent the direction and relative magnitudes of the motions of the air particles in various portions of a complete wave.

FIG. 351. Illustration of sound waves

At the end of n vibrations the first disturbance will have reached a distance n wave lengths from the fork, and each wave between this point and the fork will consist of a condensation and a rarefaction, so that sound waves may be said to consist of a series of condensations and rarefactions following one another through the air in the manner shown in Fig. 351.

Wave length may now be more accurately defined as *the distance between two successive points of maximum condensation* (b and f, Fig. 351) *or of maximum rarefaction* (d and h, Fig. 351).

385. Water-wave analogy. Condensations and rarefactions of sound waves are analogous to the familiar crests and troughs of water waves. Thus, the wave length of such a series of waves as that shown in Fig. 352 is defined as the distance bf between two crests, or the distance dh, or ae, or cg, or mn, between any two points which are in the same condition, or *phase*, of disturbance. The crests (the shaded portions, which are above the natural level of the water) correspond exactly to the condensations of sound waves

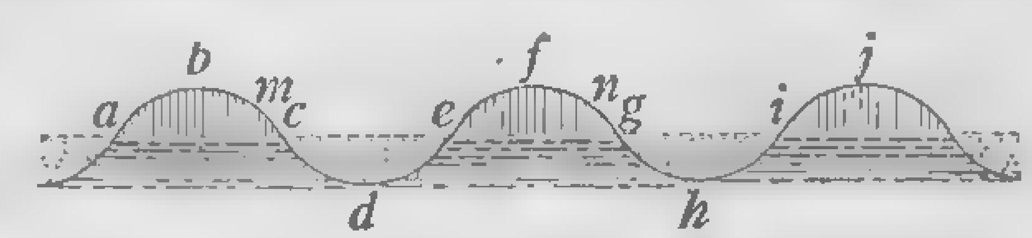


FIG. 352. Illustrating wave length of water waves

(the portions of air which are above the natural density). The troughs (the dotted portions) correspond to the rarefactions of sound waves (the portions of air which are below the natural density). But the analogy breaks down at one point, for in water waves the motion of the particles is transverse to the direction of propagation, whereas in sound waves, as shown in § 384, the particles move back and forth *in* the line of propagation of the wave. *Water waves are therefore called transverse waves, and sound waves in air are called longitudinal waves.*

386. Distinction between musical sounds and noises. Let a current of air from a $\frac{1}{8}$-inch nozzle be directed against a row of forty-eight equidistant $\frac{1}{4}$-inch holes in a metal or cardboard disk, mounted as in Fig. 353 and set into rotation either by hand or by an electric motor. A very distinct musical tone will be produced. Then let the jet of air be directed against a second row of forty-eight holes, which differs from the first only in that the holes are spaced irregularly instead of regularly about the circumference of the disk. The musical character of the tone will altogether disappear.

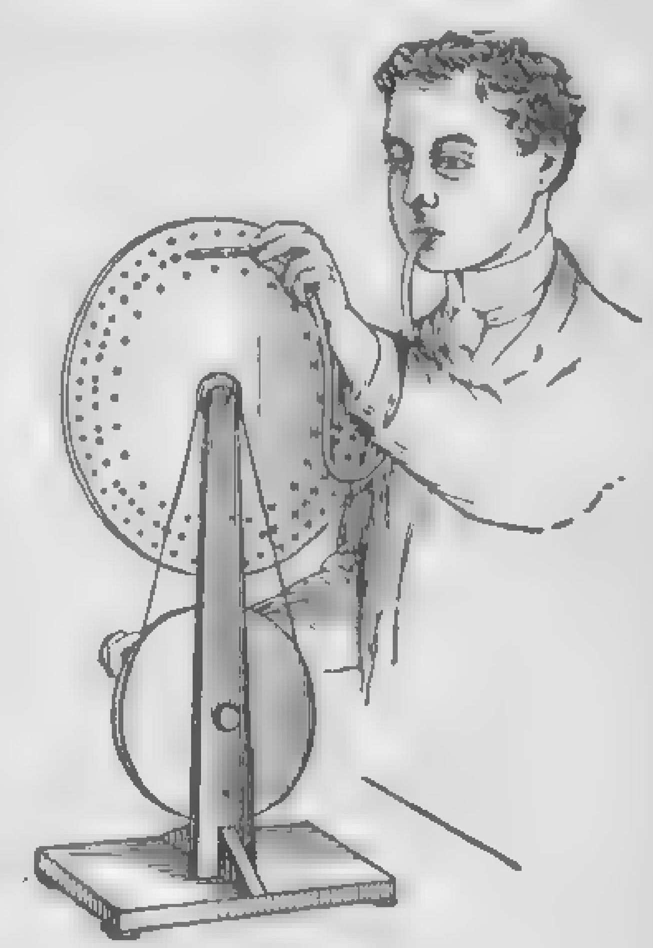


Fig. 353. Regularity of pulses the condition for a musical tone

The experiment furnishes a very striking illustration of the difference between a musical sound and a noise. *Only those sounds possess a musical quality which come from sources capable of sending out pulses, or waves, at absolutely regular intervals.*

387. Pitch. While the apparatus of the preceding experiment is rotating at constant speed, let a current of air be directed first against the outside row of regularly spaced holes and then suddenly turned against the inside row, which is also regularly spaced but which contains a smaller number of holes. The note produced in the second case will be found to have a markedly lower pitch than the other one. Again let the jet of air be directed against one particular row, and let the speed of rotation be changed from very slow to very fast. The note produced will gradually rise in pitch.

We conclude, therefore, that *the pitch of a musical note depends simply upon the number of pulses which strike the ear per second.* If the sound comes from a vibrating body, *the pitch of the note depends upon the rate of vibration of the body, and this in turn determines the length of the wave as shown by the relation $v = nl$.*

388. The Doppler effect. When a rapidly moving train rushes past an observer, he notices a very distinct and sudden change in the pitch of the bell as the engine passes him, the pitch being higher as the engine approaches than as it recedes. The explanation is as follows: The bell sends out pulses at exactly equal intervals of time. As the train is approaching, however, the pulses reach the ear at shorter intervals than the intervals between emissions, since the train comes toward the observer between two successive emissions. But as the train recedes, the interval between the receipt of pulses by the ear is longer than the interval between emissions, since the train is moving away from the ear during the interval between emissions. Hence the pitch of the bell is higher during the approach of the train than during its recession. This phenomenon of the change in pitch of a note proceeding from an approaching or receding body is known as *the Doppler effect.*

389. Loudness. The loudness or intensity of a sound depends upon the rate at which energy is communicated by it to the tympanum of the ear; that is, under the usual condition of hearing, *loudness depends upon the intensity of the forward and backward motion of the air lying close to the drum of the ear,* and this in turn is determined by the distance of the source and the amplitude of its vibration, provided the sound is transmitted through a still, homogeneous medium.

If a given sound pulse is free to spread equally in all directions, at a distance of 100 feet from the source the same energy must be distributed over a sphere of four times as large an area as at a distance of 50 feet. Hence under these ideal conditions *the intensity of a sound varies inversely as the*

11.30 ft/sec 20°C.

square of the distance from the source. But when sound is confined within a tube so that the energy is continually communicated from one layer to another of equal area, it will travel to great distances with little loss of intensity. This explains the efficiency of speaking tubes and megaphones.

SUMMARY. All sounds arise from motion of matter.

Sound is transmitted by solids, liquids, and gases, but not through a vacuum.

Relation of velocity, wave length, and frequency is given by $v = nl$.

Musical sounds come from regularity of vibration; noises, from irregular pulses.

Pitch depends upon number of vibrations per second.

Loudness depends upon the amplitude of the vibrations.

QUESTIONS AND PROBLEMS

1. When a long column of marchers is following a band, it is observed that those in the rear of the column are slightly out of step with those in front. Explain.

2. A thunderclap was heard $5\frac{1}{2}$ sec. after the accompanying lightning flash was seen. How far away did the flash occur, the temperature at the time being 20° C.?

3. A blow struck with a hammer on a steel cable was heard through the cable in .2 second and through the air 2.8 seconds later. The temperature was 18° C. (1) How far away was the blow struck? (2) What was the velocity of sound in the cable?

4. Since the music of an orchestra reaches a distant hearer without confusion of the parts, what may be inferred as to the relative velocities of the notes of different pitch?

5. What is the relation between pitch and wave length? How is this made evident by the fact noted in question 4?

6. If the tone of a man's voice has a frequency of 160, how long are the waves which are produced when he speaks in air at a temperature of 20° C.?

7. If we increase the amplitude of vibration of a guitar string, what effect has this upon the amplitude of the wave? upon the loudness? upon the length of the wave? upon the pitch?

8. Why does the sound die away very gradually after a bell is struck?

9. What is the relative loudness of the sound of the discharge of a gun as heard by A a mile from the gun and as heard by B a quarter of a mile from the gun?

10. Explain the principle of the ear trumpet.

11. Explain why the pitch of a locomotive whistle or of an automobile horn suddenly becomes lower just after the locomotive or automobile rushes past you.

Reflection, Reënforcement, and Interference

390. Echo. That a sound wave in hitting a wall undergoes reflection is shown by the familiar phenomenon of echo. The roll of thunder is caused by successive reflections of the original sound from clouds and other surfaces which are at different distances from the observer.

In ordinary rooms the walls are so close that the reflected waves return before the effect of the original sound on the ear has died out. Consequently the echo blends with and strengthens the original sound instead of interfering with it. This is why, in general, a speaker may be heard so much better indoors than in the open air. Since the ear cannot appreciate successive sounds as distinct if they come at intervals shorter than a tenth of a second, it will be seen from the fact that sounds travel a little more than 100 feet in a tenth of a second that a wall which is nearer than about 50 feet cannot possibly produce a perceptible echo. In rooms which are large enough to give rise to troublesome echoes the wall should be covered with some absorbent material.

Whispering galleries such as the dome of the Capitol at Washington are merely rooms so shaped that sound foci are produced by the concentration of reflected waves from the walls.

391. Resonance. Resonance is the *reënforcement* or *intensification* of sound because of the union of *direct* and *reflected* waves.

Thus, let one prong of a vibrating tuning fork, which makes, for example, 512 vibrations per second, be held over the mouth of a tube an inch or so in diameter, arranged as in Fig. 354, so that as the vessel A is raised or lowered the height of the water in the tube may be adjusted at will. It will be found that as the position of the water is slowly lowered from the top of the tube a very marked reënforcement of the sound will occur at a certain point.

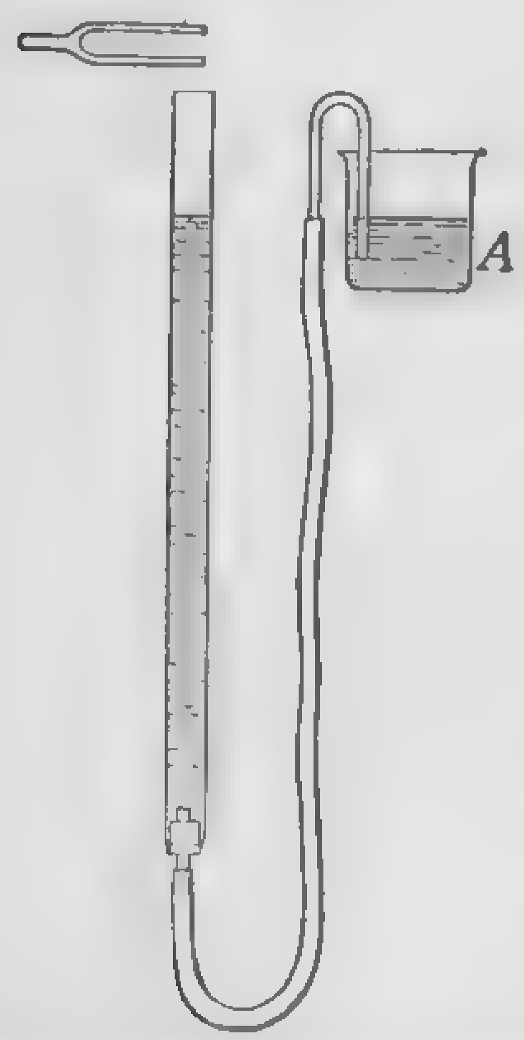


FIG. 354. Illustrating resonance

Let other forks of different pitch be tried in the same way. It will be found that the lower the pitch of the fork, the lower must be the water in the tube in order to get the best reënforcement. This means that the longer the wave length of the note which the fork produces, the longer must be the air column in order to obtain resonance.

We conclude, therefore, that *a fixed relation exists between the wave length of a note and the length of the air column which will reënforce it.*

392. Best resonant length of a closed pipe. If we calculate the wave length of the note of the fork by dividing the speed of sound by the vibration rate of the fork, we shall find that, in every case, *the length of air column which gives the best response is approximately one-fourth wave length.* The reason for this is evident when we consider that the length must be such as to enable the reflected wave to return to the mouth just in time to unite with the direct wave which is at that instant being sent off by the prong. Thus, when the prong is first starting down from the position A (see Fig. 355), it starts the beginning of a condensation down the tube. If this motion is to return to the mouth just in time to unite with the direct

FIG. 355. Resonant length of a closed pipe is one-fourth wave length

wave sent off by the prong, it must get back at the instant the prong is starting up from the position C. That is, the pulse must go down the tube and come back again while the prong is making a half vibration. This means that the path down and back must be a half wave length, and hence that the length of the tube must be a fourth of a wave length.

From the above analysis it will appear that there should also be resonance if the reflected wave does not return to the mouth until the fork is starting back the second time from C, that is, at the end of one and one-half vibrations instead of a half vibration. The distance from the fork to the water and back would then be one and one-half wave lengths; that is, the water surface would be one-half wave length farther down the tube than at first. The tube length would, therefore, now be three fourths of a wave length.

Let the experiment be tried. A similar response will be found, as predicted, a half wave length farther down the tube. This response will be somewhat weaker than before, as the wave has lost some of its energy in traveling a long distance through the tube. It may be shown in a similar way that there will be resonance where the tube length is $\frac{5}{4}$, $\frac{7}{4}$, or indeed any odd number of quarter wave lengths.

393. Best resonant length of an open pipe. Let the same tuning fork which was used in § 392 be held in front of an open pipe 8 or 10 inches long, the length of which is made adjustable by slipping back and forth over it a tightly fitting roll of writing paper (Fig. 356). It will be found that for one particular length this open pipe will respond quite as loudly as did the closed pipe, but *the responding length will be found to be just twice as great as before.* Other resonant lengths can be found when the tube is made twice, three times, etc. as long.

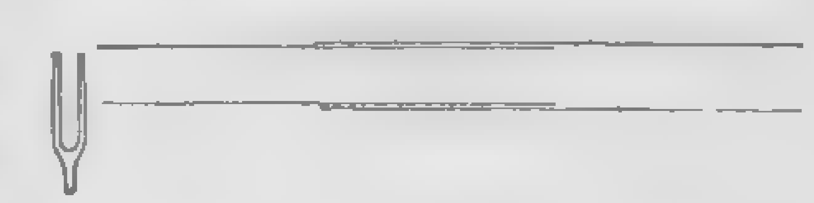


FIG. 356. Resonant length of an open pipe is one-half wave length

We learn, then, that *the shortest resonant length of an open pipe is one-half wave length, and that there is resonance at any multiple of a half wave length.*

The fact that the shortest resonant length of the open pipe is just twice that of the closed one is the experimental proof that a condensation, upon reaching the open end of a pipe, is reflected as a rarefaction. This means that when the lower end of the tube of Fig. 355 is open, a condensation upon reaching it suddenly expands. In consequence of this expansion the new pulse which begins at this instant to travel back through the tube is one in which the particles are moving down instead of up; that is, the particles are moving in a direction opposite to that in which the wave is traveling. This is always the case in a rarefaction (see Fig. 350). In order then to unite with the motion of the prong this downward motion of the particles must get back to the mouth when the prong is just starting down from *A* the second time; that is, *after one complete vibration of the prong.* This shows why the pipe length is one-half wave length. Fig. 357 summarizes what we have learned concerning the lengths of both closed and open pipes.

FIG. 357. Closed and open pipes which respond to the same fork

394. Resonators. If the vibrating fork at the mouth of the tubes in the preceding experiments is replaced by a *train of waves* coming from a distant source, precisely the same analysis leads to the conclusion that the waves reflected from the bottom of the tube will reënforce the oncoming waves when the length of the tube is any odd number of quarter wave lengths in the case of a closed pipe, or any number of half wave lengths in the case of an open pipe. It is clear, therefore, that every air chamber will act as a resonator for trains of waves of a *certain* wave length. This is why a conch shell held to the ear is always heard to hum with a particular note. Feeble waves which produce no impression upon the unaided ear gain sufficient strength when reënforced by the shell to become audible. When the air chamber is of irregular form

it is not usually possible to calculate to just what wave length it will respond, but it is always easy to determine experimentally what particular wave length it is capable of reënforcing. The resonators on which tuning forks are mounted are air chambers which are of just the right dimensions to respond to the note given out by the fork.

395. Forced vibrations; sounding boards. Let a tuning fork be struck and held in the hand. The sound will be entirely inaudible except to those quite near. Let the base of the sounding fork be pressed firmly against the table. The sound will be found to be enormously intensified. Let another sounding fork of different pitch be held against the same table. Its sound will also be reënforced. In this case, then, the table intensifies the sound of any fork which is placed against it, whereas an air column of a certain size can intensify only a single note.

The cause of the response in the two cases is wholly different. In the last case the vibrations of the fork are transmitted through its base to the table top and force the latter to vibrate in its own period. The vibrating table top, on account of its large surface, sets a comparatively large mass of air into motion and therefore sends a wave of great intensity to the ear, but the fork alone, with its narrow prongs, was not able to impart much energy to the air. Vibrations like those of the table top are called *forced* because they can be produced with any fork, no matter what its period. Sounding boards in pianos and other stringed instruments act precisely as does the table top in this experiment; that is, they are set into forced vibrations by any note of the instrument and reënforce it accordingly.

396. Beats. Since two sound waves are able to unite so as to reënforce each other, it ought also to be possible to make them unite so as to interfere with or destroy each other. In other words, under the proper conditions *the union of two sounds ought to produce silence.*

Let two mounted tuning forks of the same pitch be set side by side, as in Fig. 358. Let the two forks be struck in quick succession with a soft mallet, for example, a rubber stopper on the end

of a rod. The two notes will blend and produce a smooth, even tone. Then let a piece of wax or a small coin be stuck to a prong of one of the forks. This diminishes slightly the number of vibrations which this fork makes per second, since it increases its mass. Again, let the two forks be sounded together. The former smooth tone will be replaced by a throbbing, or pulsating, one. This is caused by the alternate destruction and reënforcement of the sounds produced by the two forks. This pulsation is called the phenomenon of *beats.*

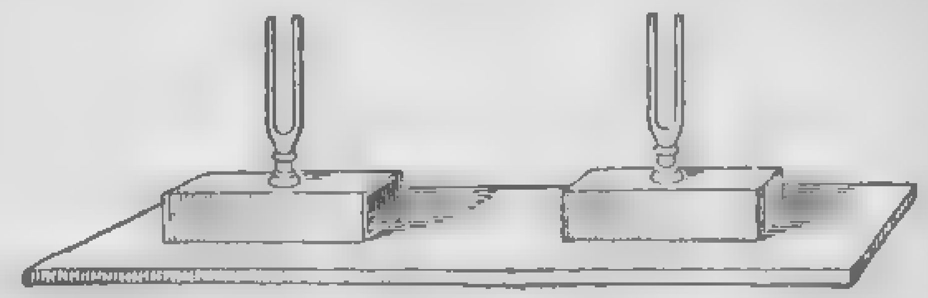


FIG. 358. Arrangement of forks for beats

The mechanism of the alternate destruction and reënforcement may be understood from the following. Suppose that one fork makes 256 vibrations per second (see the dotted line AC in Fig. 359), while the other makes 255 (see the heavy line AC). If at the beginning of a given second the two forks are swinging *together*, so that they simultaneously send out condensations to the observer, these condensations will of course unite so as to produce a double effect upon the ear (see A', Fig. 359). Since one fork gains one complete vibration per second over the other, at the end of the second considered the two forks will again be vibrating together, that is, sending out condensations which add their effects as before (see C'). In the middle of this second, however, the two forks are vibrating in opposite directions (see B); that is, one is sending out rarefactions while the other sends out condensations. At the ear of the observer the union of the rarefaction (backward motion of the air particles) produced by one fork with the condensation (forward motion) produced by the other results in no motion at all, if the two motions have

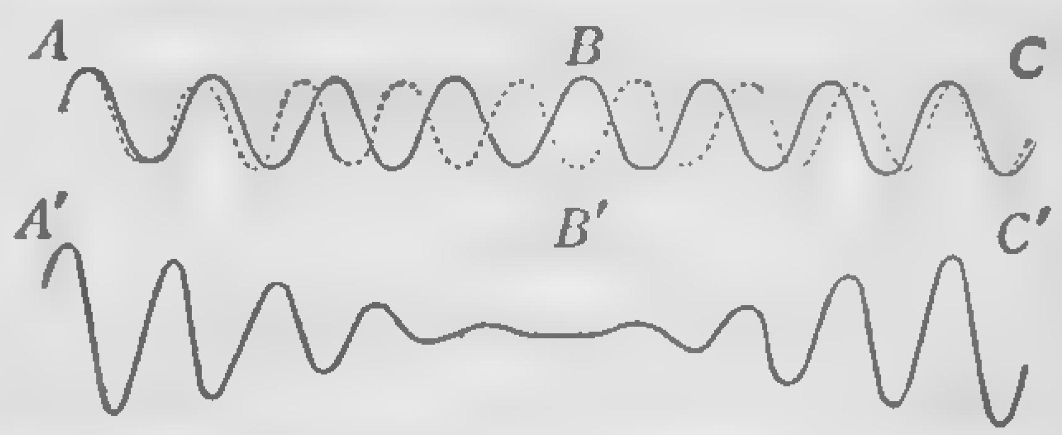


FIG. 359. Graphical illustration of beats

the same energy; that is, *in the middle of the second the two sounds have united to produce silence* (see B'). It will be seen from the above that *the number of beats per second is equal to the difference in the vibration numbers of the two forks.*

To test this conclusion, let more wax or a heavier coin be added to the weighted prong; the number of beats per second will be increased. Diminishing the weight will reduce the number of beats per second.

In tuning a piano the double and triple strings are brought into unison by tuning so as to eliminate beats.

397. Interference of sound waves by reflection. Let a thin cork about an inch in diameter be attached to one end of a brass rod from one to two meters long. Let this rod be clamped firmly

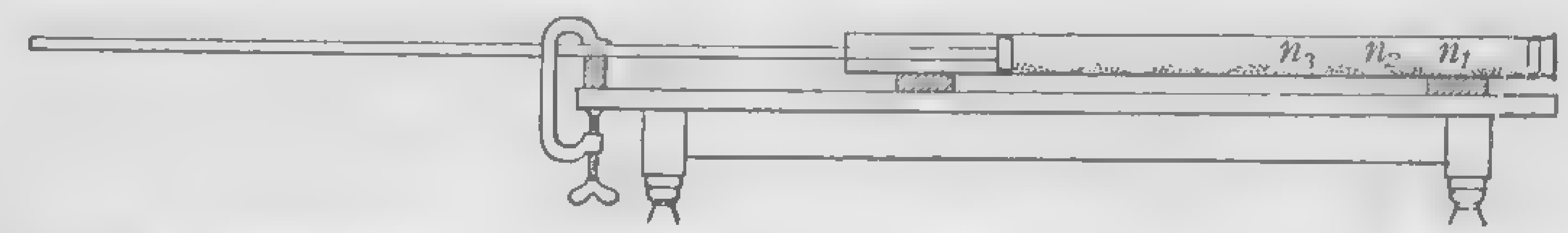


FIG. 360. Interference of advancing and retreating trains of sound waves

in the middle, as in Fig. 360. Let a piece of glass tubing a meter or more long and from an inch to an inch and a half in diameter be slipped over the cork. Let the end of the rod be stroked longitudinally with a well-resined cloth. A loud, shrill note will be produced.

This note is produced by the slipping of the resined cloth over the surface of the rod, which sets the latter into longitudinal vibrations, so that its ends impart alternate condensations and rarefactions to the layers of air in contact with them. As soon as this note is started the cork dust inside the tube will be seen to be intensely agitated. If the effect is not marked at first, a slight slipping of the glass tube forward or back will bring it out. Upon examination it will be seen that the agitation of the cork dust is not uniform, but at regular intervals throughout the tube there will be regions of complete rest, n_1, n_2, n_3, etc., separated by regions of intense motion.

The points of rest correspond to the positions in which the reflected train of sound waves returning from the end of the tube neutralizes the effect of the advancing train passing

down the tube from the vibrating rod. The points of rest are called *nodes*, the intermediate portions *loops* or *antinodes.* The distance between these nodes is one-half wave length, for at the instant that the first wave front a_1 (Fig. 361) reaches the end of the tube it is reflected and starts back toward R. Since at this instant the second wave front a_2 is just one wave length to the left of a_1, the two wave fronts must meet each other at a point n_1, just one-half wave length from the end of the tube. The exactly equal and opposite motions of the particles in the two wave fronts exactly neutralize each other. Hence the point n_1 is a point of no motion, that is, a node.

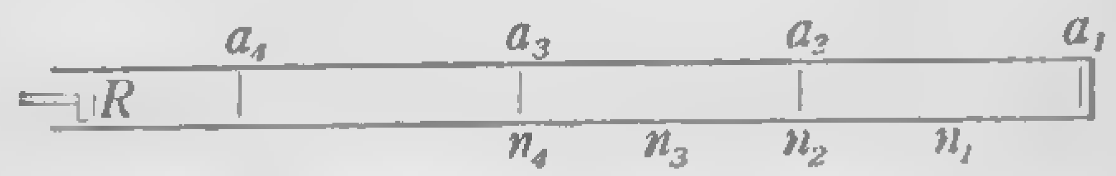
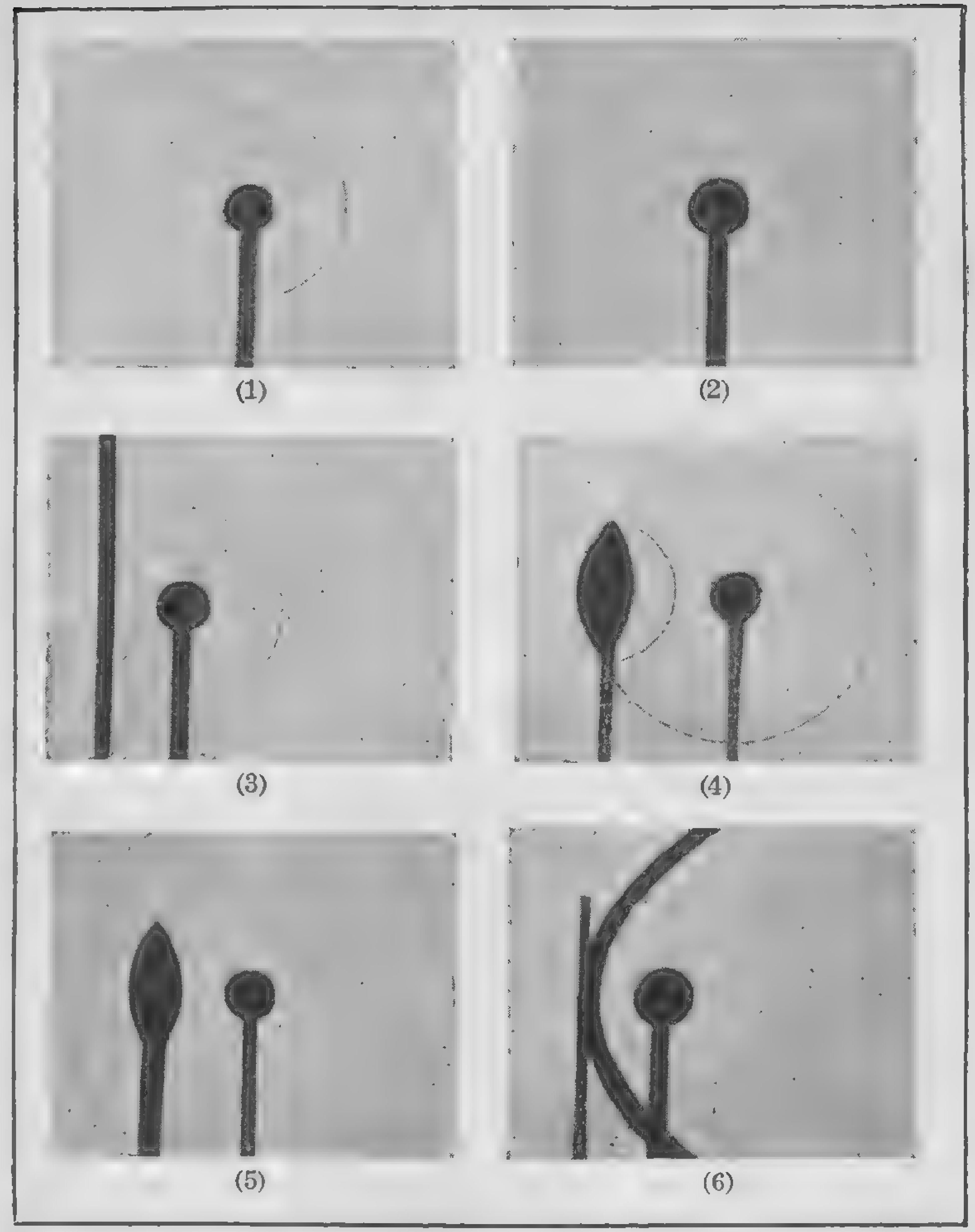


FIG. 361. Distance between nodes is one-half wave length

Again, at the instant that the reflected wave front a_1 met the advancing wave front a_2 at n_1, the third wave front a_3 was just one wave length to the left of n_1. Hence, as the first wave front a_1 continues to travel back toward R it meets a_3 at n_2, just one-half wave length from n_1, and produces there a second node. Similarly, a third node is produced at n_3, one-half wave length to the left of n_2, etc. Thus *the distance between two nodes must always be just one half the wave length of the waves in the train.*

In the preceding discussion it has been assumed that the two oppositely moving waves are able to pass through each other without either of them being modified by the presence of the other. That two opposite motions are transferred in just this manner through a medium consisting of elastic particles may be shown by the following experiment with the row of balls used in § 381.

Let the ball at one end of the row be raised a distance of, say, two inches and the ball at the other end raised a distance of four inches. Then let both balls be dropped simultaneously against the row. The two opposite motions will pass through each other in the row altogether without modification, the larger motion appearing at the end opposite to that at which it started, and the smaller likewise.



PHOTOGRAPHS OF SOUND WAVES HAVING THEIR ORIGIN IN AN ELECTRIC SPARK BEHIND THE MIDDLE OF THE BLACK DISK

(1), a spherical sound wave. (2), the same wave .00007 second later. (3), a wave reflected from a plane surface, curvature unchanged. (4), a wave reflected from a convex surface, curvature increased. (5), the source at the focus of a SO_2 lens. The photograph shows, first, the original wave on the right; second, the reflected wave, with its increased curvature; and third, the transmitted plane wave. (6), source at focus of a concave mirror; the reflected wave is plane. (Taken by Professor A. L. Foley and Wilmer H. Souder, of the University of Indiana)

AN AID TO THE DEAF: THE AUDIPHONE

Through use of a device which is essentially a very small but highly sensitive telephone system, science has rendered inestimable aid to those having impaired hearing. The picture at the left shows fastened to a pocket the small device (a carbon microphone) which receives the sound. Attached to the ear is the tiny receiver. A two-stage vacuum-tube amplifier with batteries (not here shown) is used to intensify without distortion the microphone impulses. The picture at the right shows two of the small receivers, each about the diameter of a cent, attached to hard-rubber earpieces, each of which is made from a plaster mold of the user's ear. The remarkable efficiency of the diminutive receiver is largely owing to the use in it of permalloy

Another and more complete analogy to the condition existing within the tube of Fig. 360 may be had by simply vibrating one end of a two-meter or three-meter rope, as in Fig. 362. The trains of advancing and reflected waves which continuously travel through each other up and down the rope will unite so as to form a series of nodes and loops. The nodes at c and e are the points at which the advancing and reflected waves are always urging the cord equally in opposite directions. The distance between them is one half the wave length of the train sent down the rope by the hand.

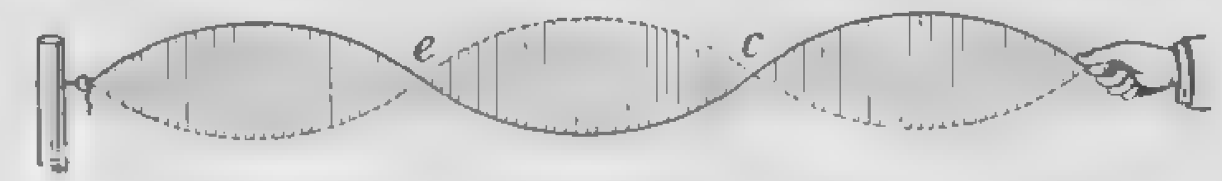


FIG. 362. Nodes and loops in a cord

SUMMARY. The length of the shortest resonant closed pipe is one-fourth wave length. (There is also resonance at any odd multiple of this length.)

The length of the shortest resonant open pipe is one-half wave length. (There is also resonance at any multiple of this length.)

Musical beats are caused by the alternate reënforcement and interference of two sets of wave trains differing in wave length, the number of beats per second being the difference in the two frequencies.

QUESTIONS AND PROBLEMS*

1. Why do the echoes which are prominent in empty halls often disappear when the hall is full of people?

2. Four seconds after a cannon was fired an echo of the report was heard from a distant iceberg. At what distance from the cannon was the iceberg, the temperature being 0° C.?

3. A gunner hears an echo $5\frac{1}{2}$ sec. after he fires. How far away was the reflecting surface, the temperature of the air being 20° C.?

4. Account for the sound produced by blowing across the mouth of an empty bottle. The bottle may be tuned to different pitches by adding more or less water. Explain.

5. Explain the roaring sound heard when a sea shell, a tumbler, or an empty tin can is held to the ear.

* Supplementary questions and problems for Chapter XVI are given in the Appendix.

6. State clearly the meaning of resonance and the meaning of forced vibration, and point out the difference between them.

7. What is the length of the shortest closed tube that will act as a resonator to a fork whose rate is 427 per second? (Temperature = 20° C.)

8. The shortest closed air column that gave resonance with a tuning fork was 32 cm. Find the rate of the fork if the speed of sound was 340 m. per second.

9. Find the number of vibrations per second of a fork which produces resonance in a closed pipe 1 ft. long; in an open pipe 1 ft. long. (Take the speed of sound as 1130 ft. per second.)

10. What change, if any, is produced in the tone of an organ pipe by a rise in temperature? Give reason for your answer.

11. Two tuning forks, one of which has a frequency of 256 per second, emit 5 beats per second when sounded simultaneously. What are the possible rates of vibration of the other fork?

12. A standard tuning fork of frequency 256 gives 4 beats per second when sounded with another fork. When a piece of wax is attached to the standard fork the number of beats is reduced to 3 per second. What is the frequency of the other fork?

CHAPTER XVII

PROPERTIES OF MUSICAL SOUNDS

MUSICAL SCALES

398. Physical basis of musical intervals. Let a metal or cardboard disk 10 or 12 inches in diameter be provided with four concentric rows of equidistant holes, the successive rows containing respectively 24, 30, 36, and 48 holes (Fig. 363). The holes should be about $\frac{1}{4}$ inch in diameter, and the rows should be about $\frac{1}{2}$ inch apart. Let this disk (a siren) be placed in the rotating apparatus and a constant speed imparted. Then let a jet of air be directed, as in § 386, against each row of holes in succession. It will be found that the musical sequence *do, mi, sol, do'* results. If the speed of rotation is increased, each note will rise in pitch, but the sequence will remain unchanged.

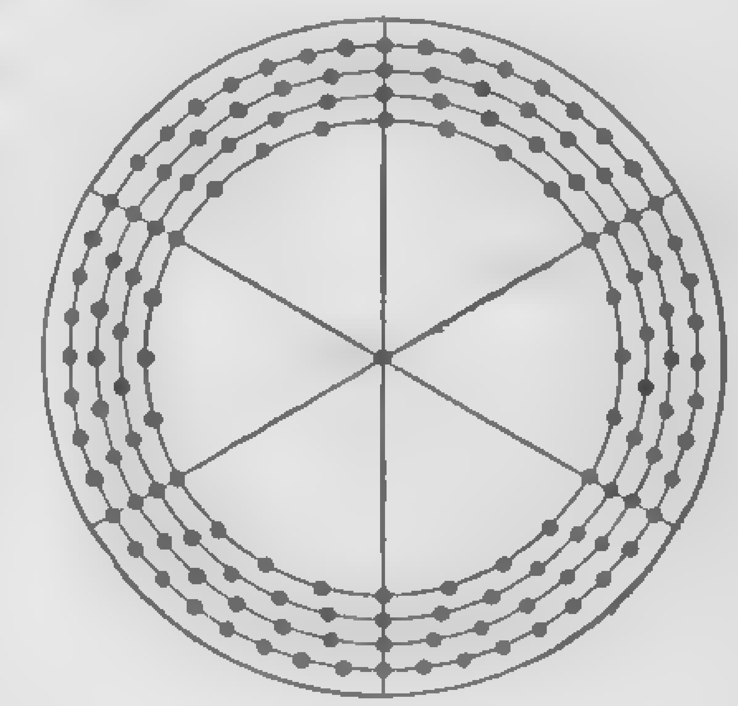


FIG. 363. Siren for producing musical sequence *do, mi, sol, do'*

We learn, therefore, that *the musical sequence do, mi, sol, do' consists of notes whose vibration numbers have the ratios of 24, 30, 36, 48, that is, 4, 5, 6, 8, and that this sequence is independent of the absolute vibration numbers of the tones.*

Furthermore, when two notes an octave apart are sounded together, they form the most harmonious combination which it is possible to obtain. These characteristics of notes an octave apart were recognized in the earliest times, long before anything whatever was known about the ratio of their vibration numbers. The preceding experiment showed that *this ratio is the simplest possible,* namely, 24 to 48, or 1 to 2. Again, the next easiest musical interval to produce, and the next

most harmonious combination which can be found, corresponds to the two notes commonly designated as *do, sol.* Our experiment showed that this interval corresponds to the next simplest possible vibration ratio, namely, 24 to 36, or 2 to 3. When *sol* is sounded with *do′*, the vibration ratio is seen to be 36 to 48, or 3 to 4. We see, therefore, that the three simplest possible ratios of vibration numbers, namely, 1 to 2, 2 to 3, and 3 to 4, are used in the production of the three notes *do, sol, do′*. Again, our experiment shows that another harmonious musical interval, *do, mi,* corresponds to the vibration ratio 24 to 30, or 4 to 5. We learn, therefore, that *harmonious musical intervals correspond to very simple vibration ratios.*

399. The major diatonic scale. When the three notes *do, mi, sol,* which, as seen above, have the vibration ratios 4, 5, 6, are all sounded together, they form a remarkably pleasing combination of tones. This combination was picked out and used very early in the musical development of the race. It is now known as the *major chord. The major diatonic scale is built up of three major chords* in the manner shown in the following table, where the first major chord is denoted by *1*, the second by *2*, and the third by *3*.

Syllables	*do*	*re*	*mi*	*fa*	*sol*	*la*	*si*	*do*	*re*
Letters	*C*	*D*	*E*	*F*	*G*	*A*	*B*	*C′*	*D′*
Relative vibration numbers .	24	27	30	32	36	40	45	48	54
	1		*1*		*1*				
					2		*2*		*2*
				3		*3*		*3*	

The chords *do-mi-sol* (the tonic), *sol-si-re* (the dominant), and *fa-la-do* (the subdominant) occur frequently in all music.

Standard middle-*C* forks made for physical laboratories all have the vibration number 256, which makes *A* in the physical scale $426\frac{2}{3}$. In the so-called *international pitch A* has 435 vibrations, and in the widely adopted American Federation of Musicians' pitch, 440.

400. The even-tempered scale. If *G* is taken as *do*, and a scale built up as shown above, it will be found that six of the notes in each octave in the table above can be used in this new key, but that two additional ones are required (see table below). Similarly, to build up scales, as above, in all the keys demanded by modern music would require about fifty notes in each octave. So, to compromise, the octave is divided into twelve equal intervals represented by the eight white and five black keys of a piano. How this so-called *even-tempered scale* differs from the ideal, or diatonic, scale is shown below.

Note	*C*	*D*	*E*	*F*	*G*	*A*	*B*	*C′*	*D′*	*E′*	*F′*	*G′*
Diatonic . . .	256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512	576	640	682.2	768
Diatonic key of *G*	—	—	—	—	384	*432*	480	512	576	640	*720*	768
Tempered . . .	256	287.4	322.7	341.7	383.8	430.7	483.5	512	574.8	645.4	683.4	767.6

VIBRATING STRINGS*

401. Laws of vibrating strings. Let two piano wires be stretched over a box or a board with pulleys attached so as to form a sonometer (Fig. 364). Let the weights *A* and *B* be adjusted until the two wires emit exactly the same note. The phenomenon of beats will make it possible to do this with great accuracy. Then let the bridge *D* be inserted exactly at the middle of one of the wires, and the two wires plucked in succession. The interval will be recognized at once as *do, do′*. Next let the bridge be inserted so as to make one wire two thirds as long as the other, and let the two be plucked again. The interval will be recognized as *do, sol.*

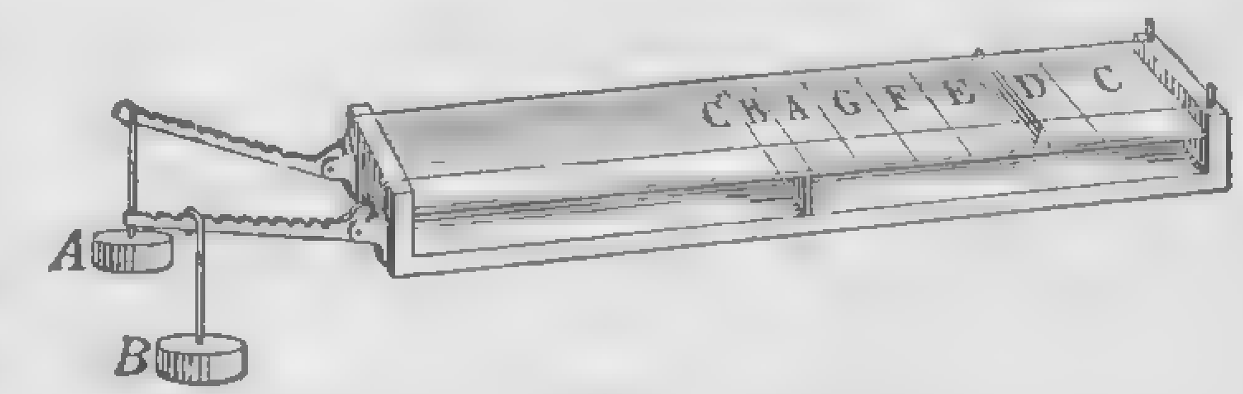


FIG. 364. The sonometer

Now it was shown in § 398 that *do′* has twice as many vibrations per second as *do*, and *sol* has three halves as many. Hence, since the length corresponding to *do′* is one half as great as the first length, and that corresponding to *sol* two

* This discussion should be followed by a laboratory experiment on the laws of vibrating strings. See, for example, Experiment 53 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

thirds as great, we conclude from this experiment that, other things being equal, *the vibration numbers of strings are inversely proportional to their lengths.*

Again, let the two wires be tuned to unison, and then let the weight A be increased until the pull which it exerts on the wire is exactly four times as great as that exerted by B. The note given out by the A wire will again be found to be an octave above that given out by the B wire.

We learn, then, that *the vibration numbers of similar strings of equal length are proportional to the square roots of their tensions.*

In stringed instruments, such as the piano, the different pitches are obtained by using strings of different length, tension, and mass per unit length.

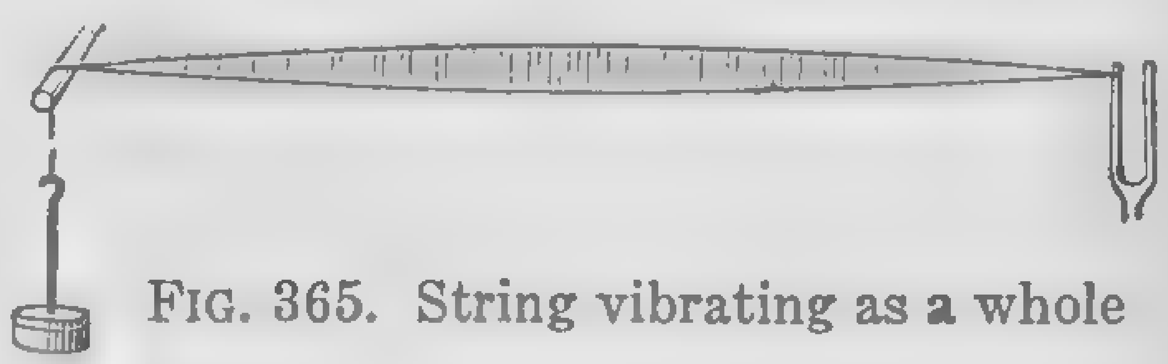


FIG. 365. String vibrating as a whole

402. Nodes and loops in vibrating strings. Let a string 1 m. long be attached to one of the prongs of a large tuning fork which makes in the neighborhood of 100 vibrations per second. Let the other end be attached as in the figure and the fork set into vibration. If the fork is not electrically driven, which is much to be preferred, it may be bowed with a violin bow or struck with a soft mallet. By making the tension of the thread, for example, proportional to the numbers 9, 4, and 1 it will be found possible to make it vibrate either as a whole, as in Fig. 365, or in two or three parts (Fig. 366).

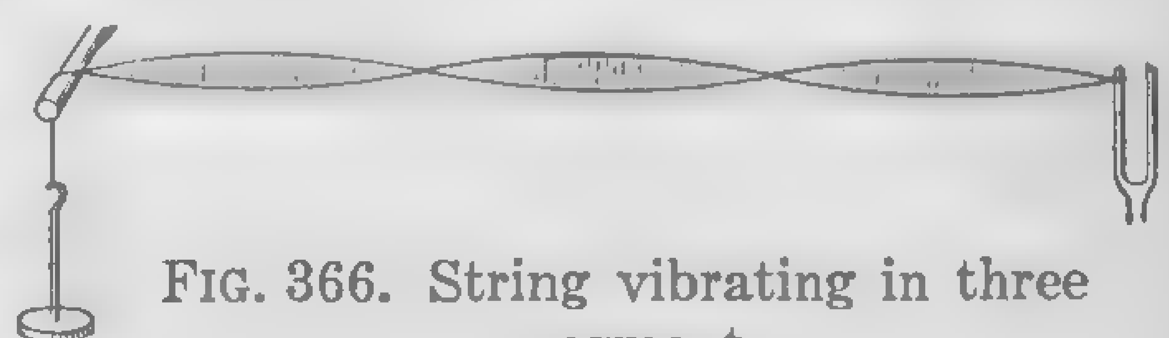


FIG. 366. String vibrating in three segments

This effect is due, as explained in § 397, to the interference of the direct and reflected waves sent down the string from the vibrating fork. But we shall show in the next section that in considering the effects of the vibrating string on the surrounding air we shall make no mistake if we think of it as

clamped at each node, and as actually vibrating in two or three or four separate parts, as the case may be.

SUMMARY. Harmonious musical intervals correspond to simple vibration ratios, the octave being 1 to 2.

A major chord consists of the vibration ratios 4, 5, 6.

The major diatonic scale is built up of three major chords.

The frequencies of similar strings are inversely as their lengths; directly as the square roots of their tensions.

QUESTIONS AND PROBLEMS

1. A certain tuning fork has a vibration frequency of 512. What is the frequency of a tuning fork whose pitch is one octave lower? one octave higher?

2. A man singing in a room at temperature 20° C. sends out a wave 9 ft. long. What is the pitch (frequency) of the note sounded?

3. Build up a diatonic scale on $C = 264$.

4. Find the wave length of the lowest note on the piano ($A_4 = 27.2$); the wave length of the highest note ($C'''' = 4137$). (Take the speed of sound as 1130 ft. per second.)

5. If middle C had 300 vibrations per second, how many vibrations would F and A have?

6. What is the wave length of international A when the speed of sound is 1131 ft. per second?

7. In what three ways do piano makers obtain the different pitches?

8. A wire 50 cm. long gives out 400 vibrations per second. How many vibrations will it give when the length is reduced to 10 cm.?

9. A wire gives out the note C when the tension on it is 4 kg. What tension will be required to give out the note G?

10. At what point must the G_1 string be pressed by the finger of the violinist in order to produce the note C?

11. If one wire has twice the length of another and is stretched by four times the stretching force, how will their vibration numbers compare?

Fundamentals and Overtones

403. Fundamentals and overtones. If the assertion made in § 402 is correct, then a string which has a node in the middle communicates to the air twice as many pulses per second as the same string when it vibrates as a whole. This may be shown conclusively as follows:

Let the sonometer wire (Fig. 364) be plucked in the middle and the pitch of the corresponding tone carefully noted. Then let the finger be touched to the middle of the wire, and the latter plucked midway between this point and the end.* The octave of the original note will be distinctly heard. Next let the finger be touched at a point one third of the wire length from one end, and the wire again plucked. The note will be recognized as *sol′*. Since we learned in § 399 that *sol′* has three halves as many vibrations as *do′*, it must have three times as many vibrations as the original note. Hence a wire which is vibrating in three segments sends out three times as many vibrations as when it is vibrating as a whole.

When a wire vibrates simply as a whole, it gives forth the lowest note which it is capable of producing. This note is called the *fundamental* or first partial of the wire. When the wire is made to vibrate in two parts, it gives forth, as has just been shown, a note an octave higher than the fundamental. This is called the *first overtone* or second partial. When the wire is made to vibrate in three parts it gives forth a note corresponding to three times the vibration number of the fundamental, namely, *sol′*. This is called the *second overtone* or third partial. When the wire vibrates in four parts, it gives forth the third overtone, which is two octaves above the fundamental. The overtones of wires are often called *harmonics*. They bear the vibration ratios 2, 3, 4, 5, 6, 7, etc. to the fundamental.†

* It is well to remove the finger almost simultaneously with the plucking.

† Some instruments, such as bells, can produce higher tones whose vibration numbers are not exact multiples of the fundamental. These notes are still called overtones, but they are not called harmonics, the latter term being reserved for the multiples. Strings produce harmonics only.

404. Simultaneous production of fundamentals and overtones. Thus far we have produced overtones only by forcing the wire to remain at rest at properly chosen points during the bowing.

Now let the wire be plucked at a point one fourth of its length from one end, *without being touched in the middle.* The tone most distinctly heard will be the fundamental; but if the wire is now touched very lightly exactly in the middle, the sound, instead of ceasing altogether, will continue, but the note heard will be an octave higher than the fundamental, showing that in this case there was superposed upon the vibration of the wire as a whole a vibration in two segments also (Fig. 367). By touching the wire in the middle the vibration as a whole was destroyed, but that in two parts remained. Let the experiment be repeated, with this difference, that the wire is now plucked in the middle instead of one fourth its length from one end. If it is now touched in the middle, the sound will cease entirely, showing that when a wire is plucked in the middle there is no first overtone superposed upon the fundamental. Let the wire be plucked again one fourth of its length from one end and careful attention given to the compound note emitted. It will be found possible to recognize both the fundamental and the first overtone sounding at the same time. Similarly, by plucking at a point one sixth of the length of the wire from one end, and then touching it at a point one third of its length from the end, the second overtone may be made to appear distinctly, and a trained ear will detect it in the note given off by the wire, even before the fundamental is suppressed by touching at the point indicated.

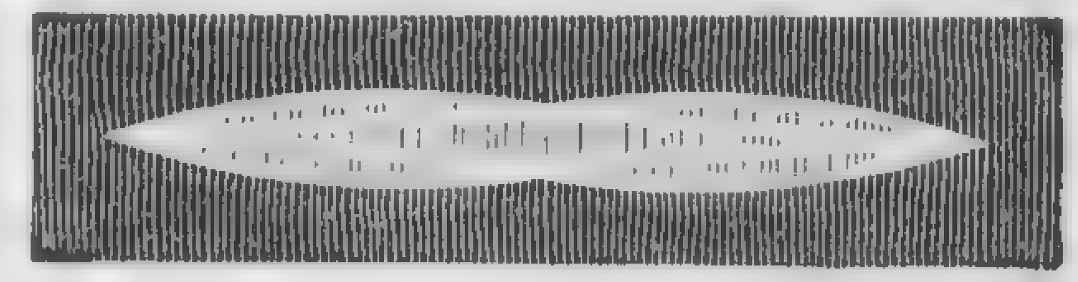


FIG. 367. A wire simultaneously emitting its fundamental and first overtone

The experiments show that in general *the note emitted by a string plucked at random is a complex one, consisting of a fundamental and several overtones, and that just what overtones are present in a given case depends on where and how the wire is plucked.*

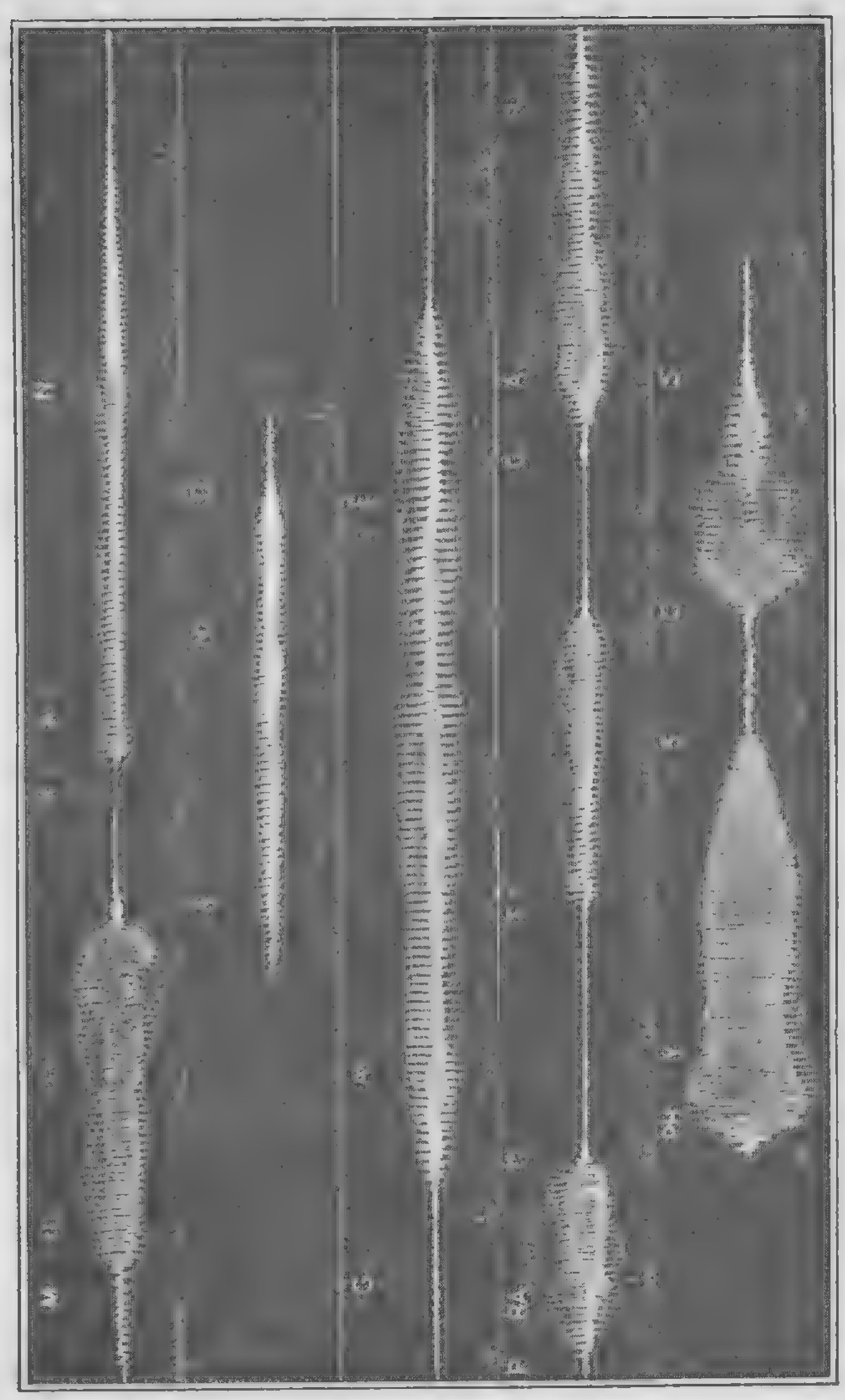
405. Quality. Let the sonometer wire be plucked first in the middle and then close to one end. The two notes emitted will have exactly the same pitch, and they may have exactly the same

loudness, but they will be easily recognized as different with respect to something which we call *quality*. The experiment of the last section shows that the real physical difference in the tones is a difference in the sorts of overtones which are mixed with the fundamental in the two cases.

Let a mounted C' fork be sounded simultaneously with a mounted C fork. The resultant tone will sound like a rich, full C, changing to a hollow C when the C' is quenched with the hand.

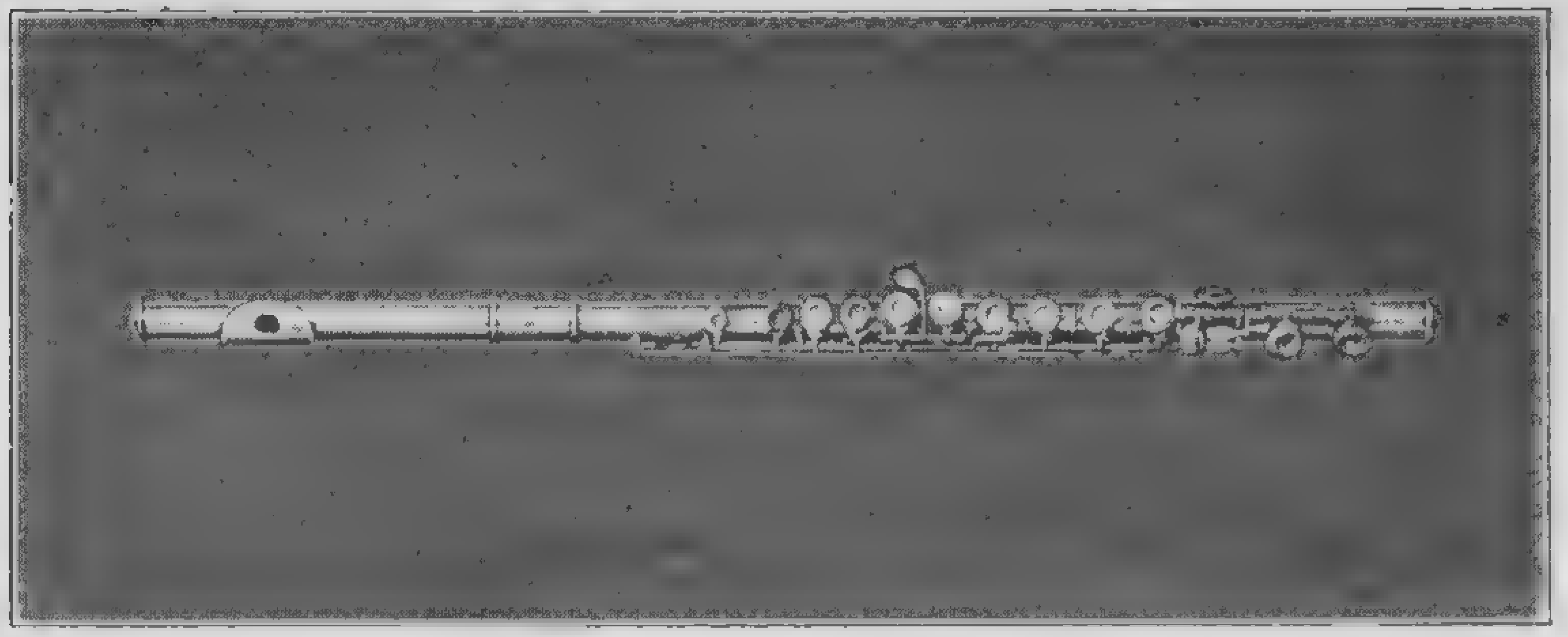
Everyone is familiar with the fact that when notes of the same pitch and loudness are sounded upon a piano, a violin, and a cornet, the three tones can be readily distinguished. The last experiments suggest that the cause of this difference lies in the fact that it is only the *fundamental* which is the same in the three cases, and that the *overtones* are different. In other words, the characteristic of a tone which we call its quality is determined simply by *the number and prominence of the overtones which are present.* If the overtones present are few and weak, and the fundamental is strong, the tone is, as a rule, soft and mellow, as when a flute is played, or a sonometer wire is plucked in the middle, or a closed organ pipe is blown gently, or a tuning fork is struck with a soft mallet. The presence of comparatively strong overtones up to the fifth adds fullness and richness to the tone. This is illustrated by the ordinary tone from a clarinet, a violin, or a piano, in which several if not all of the first five overtones have a prominent place. When overtones higher than the sixth are present, a sharp metallic quality begins to appear. This is illustrated when a tuning fork is struck, or a wire plucked, with a hard body. In order to avoid this quality the hammers which strike against piano wires are covered with felt.

406. Analysis of tones by the manometric flame. If in front of the trumpet G of the apparatus shown opposite page 349 we hold the open ends of the resonance boxes of two tuning forks, C and C', and simultaneously sound the forks, the image of the flame will be as shown at the top of Fig. 368. Here we see a complex wave form caused by a combination of

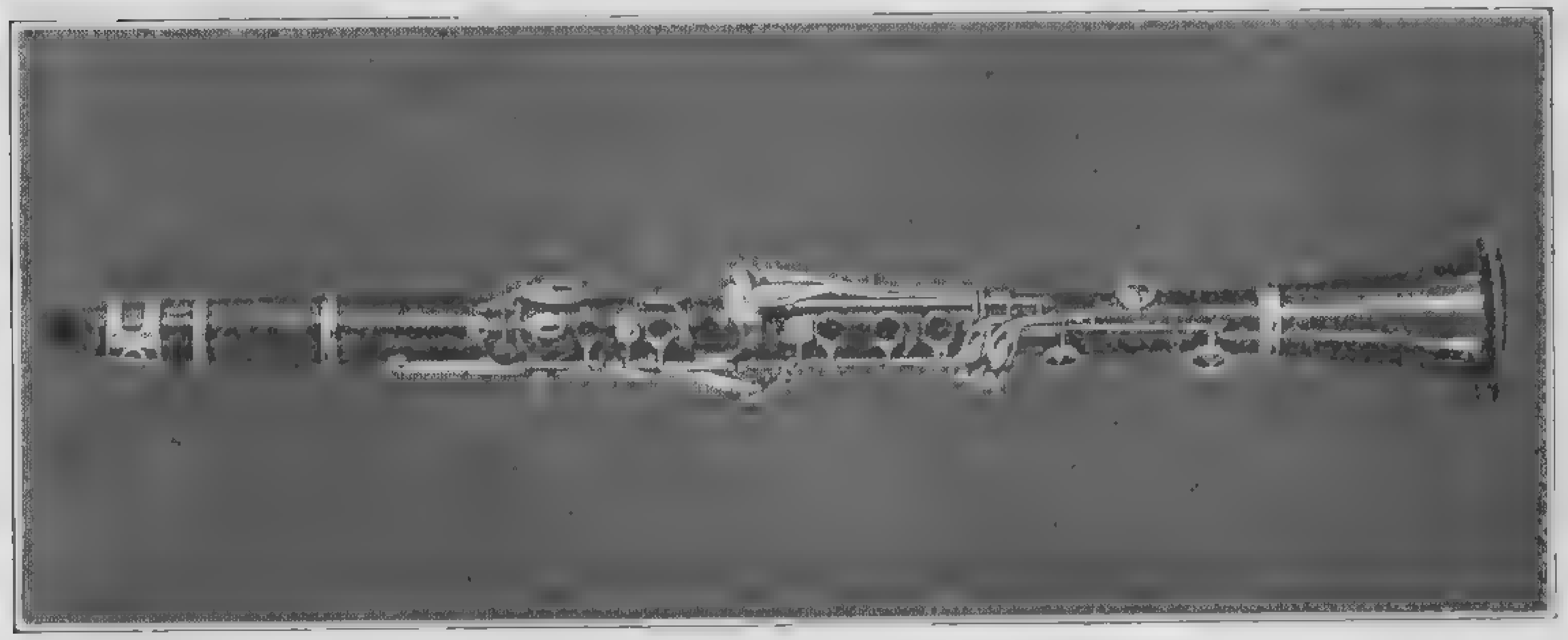


SOUND WAVES OF SPOKEN WORDS

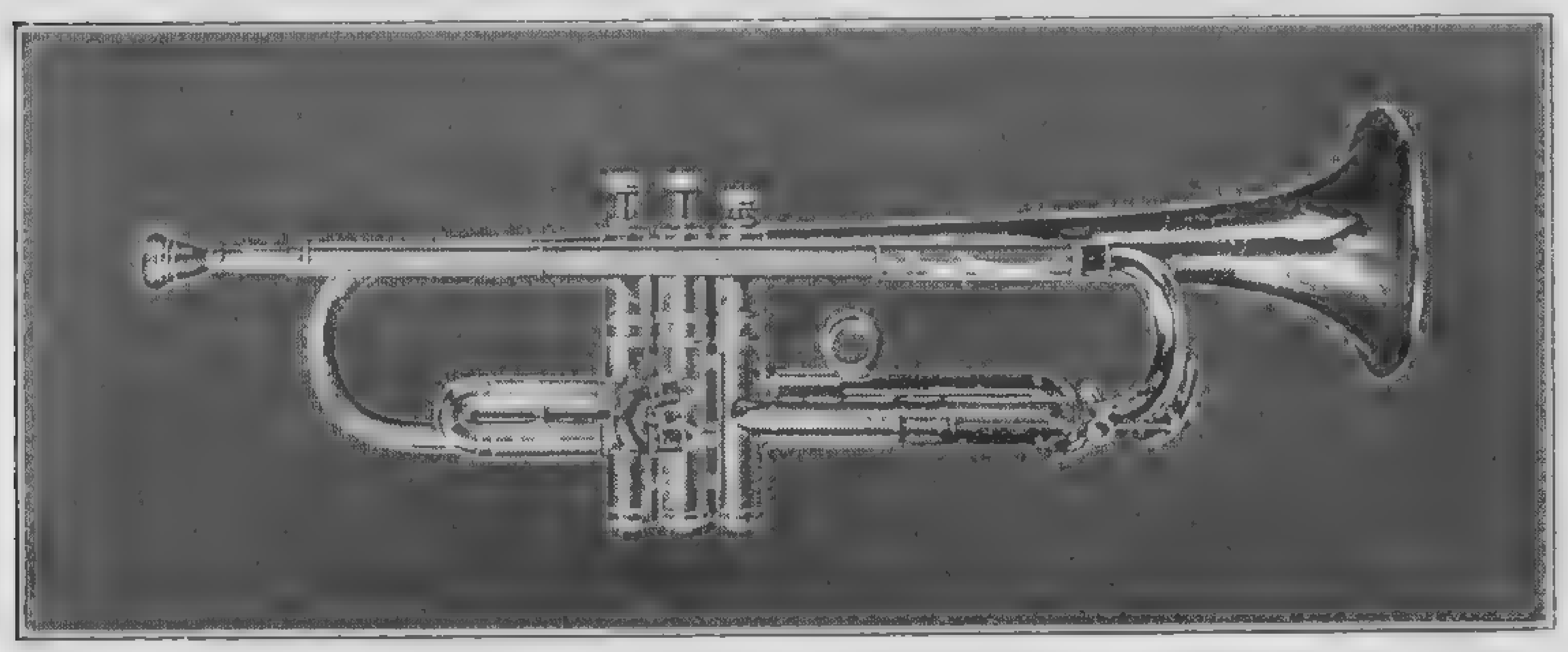
The words were spoken at a pitch of from 150 to 180. Waves cause vibrations in a diaphragm which are transferred to a mirror that reflects a beam of light to a moving film. (From a photograph by Professor D. C. Miller)



THE FLUTE: A VIBRATING-AIR-JET INSTRUMENT



THE CLARINET: A VIBRATING-REED INSTRUMENT



THE CORNET: A VIBRATING-LIP INSTRUMENT

The three different types of instruments illustrated on this page all have their characteristic quality, or wave form, owing to the different numbers and relative intensities of overtones produced by them. Their mode of tone production is discussed in §§ 414, 415, and 416

two simple tones, one the octave of the other. Any note producing this wave form is, therefore, known to consist of the fundamental with its first overtone only.

The proof that most tones are complex lies in the fact that when analyzed by the manometric flame they show figures not like those opposite page 349, which correspond to simple tones, but like those of Fig. 368, which may be produced by sounding combinations of simple tones. The last three wave forms were produced by singing the vowels *ou*, *o*, and *a* at the same pitch. The beautiful photographs opposite page 372, taken by Professor D. C. Miller, show the extraordinary complexity of spoken words.

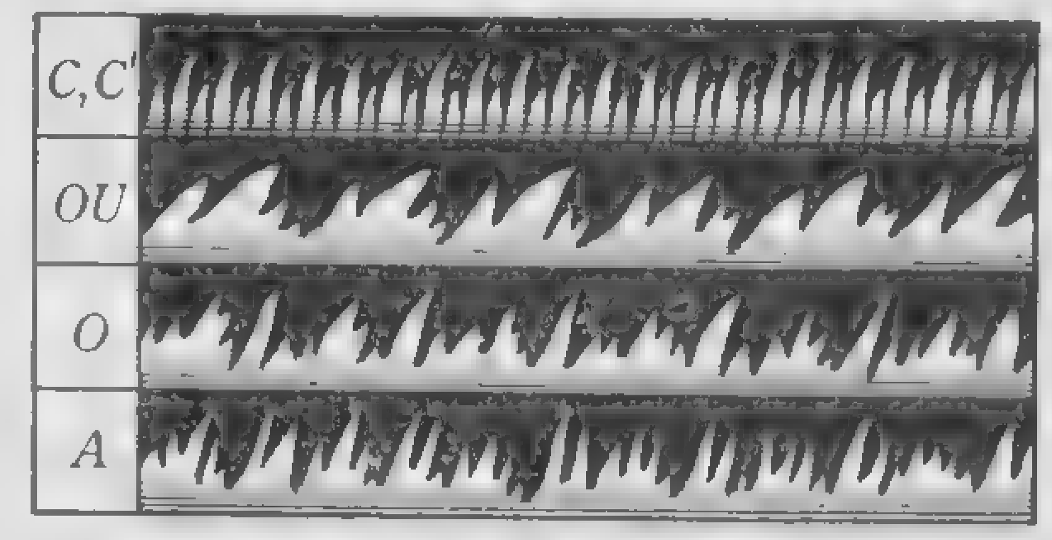


Fig. 368. Analysis of sounds with manometric flames

407. Helmholtz's experiment. If the loud pedal on a piano is held down and the vowel sounds o͞o, ī, ā, ä, ē, sung loudly into the strings, these vowels will be caught up and returned by the instrument with sufficient fidelity to make the effect almost uncanny.

It was by a method which may be considered as merely a refinement of this experiment that Helmholtz proved conclusively that quality is determined simply by the number and prominence of the overtones which are blended with the fundamental. He first constructed a large number of resonators, like that shown in Fig. 369, each of which would respond to a note of some particular pitch. By holding these resonators in succession to his ear while a musical note was sounding, he picked out the constituents of the note; that is, he found out just what overtones were present and what were their relative intensities. Then he put these con-

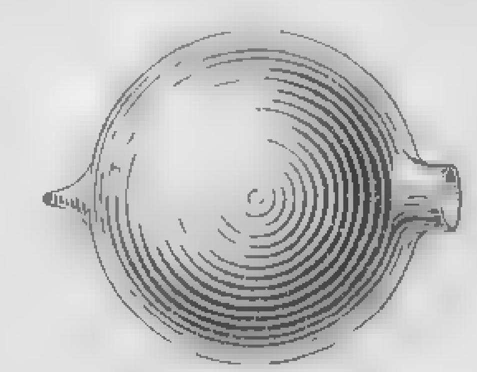


Fig. 369. Helmholtz's resonator

stituents together and reproduced the original tone. This was done by sounding simultaneously, with appropriate loudness, two or more of a whole series of tuning forks which had the vibration ratios 1, 2, 3, 4, 5, 6, 7. In this way he succeeded not only in imitating the qualities of different musical instruments but even in reproducing the various vowel sounds.

408. Sympathetic vibrations. Let two mounted tuning forks of the same pitch be placed with the open ends of their resonators facing each other. Let one be set into vigorous vibration with a soft mallet and then quickly quenched by grasping the prongs with the hand. The other fork will be found to be sounding loudly enough to be heard over a large room. Next let a penny be waxed to one prong of the second fork and the experiment repeated. When the sound of the first fork is quenched, no sound whatever will be found to be coming from the second fork.

The experiment illustrates the phenomenon of *sympathetic vibrations,* and shows what conditions are essential to its appearance. If two bodies capable of emitting musical notes have exactly the same natural period of vibration, the pulses communicated to the air when one alone is sounding beat upon the second at intervals which correspond exactly to its own natural period. Each pulse, therefore, adds its effect to that of the preceding pulses; and though the effect from a single pulse is very slight, a great number of such pulses produce a large resultant effect. In the same way a large number of very feeble pulls may set a heavy pendulum into vibration if the pulls come at intervals exactly equal to the natural period of the pendulum. But if the two sounding bodies have even a slight difference of period, the effect of the first pulses is neutralized by the effect of succeeding pulses as soon as the two bodies, on account of their difference in period, get to swinging in opposite directions.

Let notes of different pitches be sung into a piano when the dampers are lifted. The wire which has the pitch of the note sounded will in every case respond. Sing a little off the key and the response will cease.

409. Physical significance of harmony and of discord. Let two pieces of glass tubing about 1 inch in diameter and $1\frac{1}{2}$ feet long be supported vertically, as shown in Fig. 370. Let two gas jets (made by drawing down pieces of one-fourth-inch glass tubing until, with full gas pressure, the flame is about 1 inch long) be thrust inside these tubes to a height of about 3 or 4 inches from the bottom. Let the gas be turned down until the tubes begin to sing. Without attempting to discuss the part which the flame plays in the production of the sound, we wish simply to call attention to the fact that the two tones are either quite in unison or so near it that only a few beats are produced per second. Now let the length of one of the tubes be slightly increased by slipping the paper cylinder S up over its end. The number of beats will be rapidly increased until they will become indistinguishable as separate beats and will merge into a jarring, grating discord.

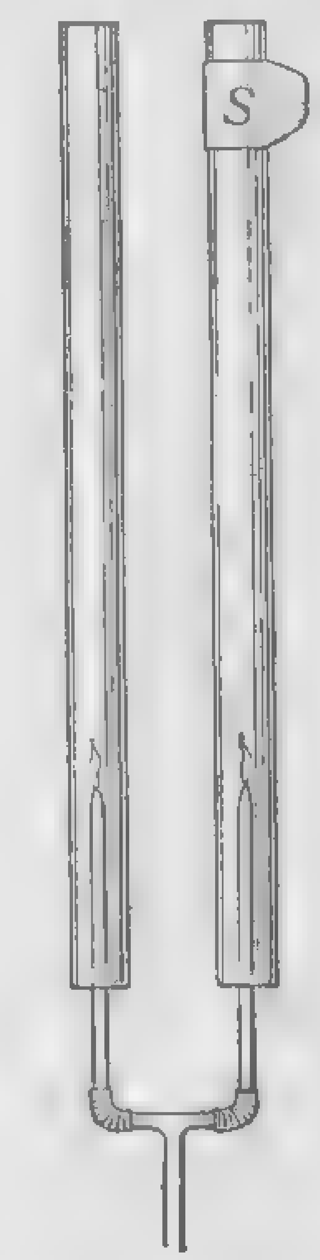


FIG. 370. Illustrating the production of discords

The experiment teaches that *discord is simply a phenomenon of beats.* If the vibration numbers do not differ by more than five or six, that is, if there are not more than five or six beats per second, the effect is not particularly unpleasant. From this point on, however, as the difference in the vibration numbers, and therefore in the number of beats per second, increases, the unpleasantness increases, and becomes worst at a difference of about thirty. Thus, the notes B and C', which differ by about thirty-two beats per second, produce about the worst possible discord. When the vibration numbers differ by as much as seventy, which is about the difference between C and E, the effect is again pleasing, or harmonious. Moreover, in order that two notes may harmonize well, it is necessary not only that the notes themselves shall not produce an unpleasant number of beats, but also that such beats

shall not arise from their overtones. Thus, *C* and *B* are very discordant, although they differ by a large number of vibrations per second. The discord in this case arises between *B* and *C′*, the first overtone of *C*.

Again, there are certain classes of instruments, of which bells are a striking example, which produce insufferable discords when even such notes as *do, sol, do′*, are sounded simultaneously upon them. This is because these instruments, unlike strings and pipes, have overtones which are not harmonics, that is, which are not multiples of the fundamental; and these overtones produce beats either among themselves or with one of the fundamentals. It is for this reason that in playing chimes the bells are struck in succession, not simultaneously.

SUMMARY. The quality of a tone is determined by the number and prominence of the overtones.

Sympathetic vibrations are possible only when the natural periods of vibration of the two bodies are exactly the same.

Discords are caused by rapid beats.

QUESTIONS AND PROBLEMS

1. A violin string is commonly bowed about one seventh of its length from one end. Why is this better than bowing in the middle?

2. What did Helmholtz prove by means of his resonators?

3. A wire gives out the note *G*. What is its fourth overtone?

4. What is the fourth overtone of *C*? the fifth overtone?

5. It is forbidden to sound certain low notes on the pipe organs of some of the cathedrals of Europe for fear of ruining one or more of the great stained-glass windows. Explain.

6. Three tuning forks give 256, 288, and 512 vibrations per second respectively. (1) Which two of these forks when sounded simultaneously will give the most pleasing effect? (2) Which two will give the most unpleasant discord? Explain.

WIND INSTRUMENTS

410. Fundamentals of closed pipes. Let a tightly fitting rubber stopper be inserted in a glass tube *a* (Fig. 371), 8 or 10 inches long and about $\frac{3}{4}$ inch in diameter. Let the stopper be pushed along the tube until, when a vibrating *C′* fork is held before the mouth, resonance is obtained as in § 392 (the length will be 6 or 7 inches). Then let the fork be removed and a stream of air blown across the mouth of the tube through a piece of tubing *b*, flattened at one end as in the figure.* The pipe will be found to emit strongly the note of the fork.

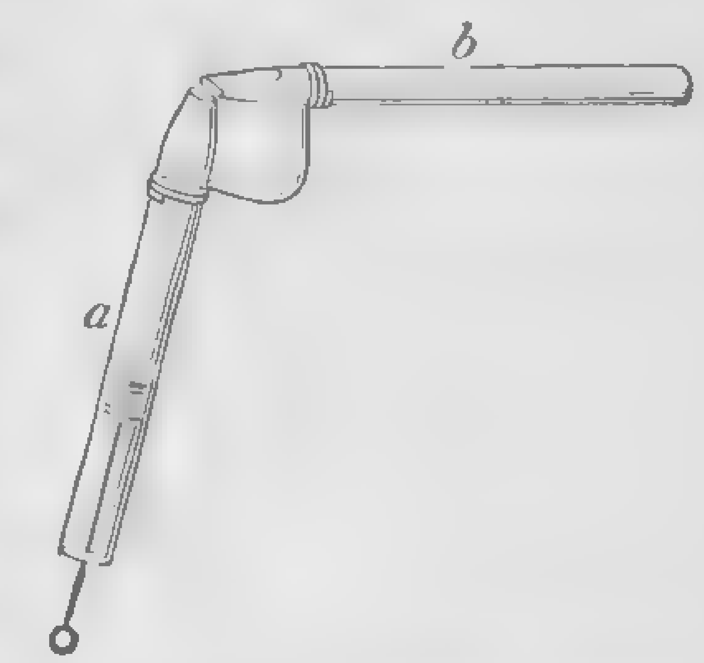


FIG. 371. Musical notes from pipes

In every case it is found that a note which a pipe may be made to emit is always a note to which it is able to respond when used as a resonator. Since, in § 392, the best resonance was found when the wave length given out by the fork was four times the length of the pipe, we learn that *when a current of air is suitably directed across the mouth of a closed pipe, it will emit a note which has a wave length four times the length of the pipe.* This note is called the *fundamental* of the pipe. It is the lowest note which the pipe can be made to produce.

411. Fundamentals of open pipes. Since we found in § 393 that the lowest note to which a pipe open at the lower end can respond is one the wave length of which is twice the pipe length, we infer that an open pipe, when suitably blown, ought to *emit* a note the wave length of which is twice the pipe length. This means that if the same pipe is blown first when closed at the lower end and then when open, the first note ought to be an octave lower than the second.

* If the arrangement of Fig. 371 is not at hand, simply blow with the lips across the edge of a piece of ordinary glass tubing within which a rubber stopper may be pushed back and forth.

Let the pipe *a* (Fig. 371) be closed at the bottom with the hand and blown; then let the hand be removed and the operation repeated. The second note will indeed be found to be an octave higher than the first.

We learn, therefore, that *the fundamental of an open pipe has a wave length equal to twice the pipe length.*

412. Overtones in pipes. It was found in § 392 that there is a whole series of pipe lengths which respond to a given fork, and that these lengths bear to the wave length of the fork the ratios $\frac{1}{4}$, $\frac{3}{4}$, $\frac{5}{4}$, etc. This is equivalent to saying that a closed pipe of *fixed* length can respond to a whole series of notes whose vibration numbers have the ratios 1, 3, 5, 7, etc. Similarly, in § 393, we found that in the case of an open pipe the series of pipe lengths which will respond to a given fork bear to the wave length of the fork the ratios $\frac{1}{2}$, $\frac{2}{2}$, $\frac{3}{2}$, $\frac{4}{2}$, etc. This, again, is equivalent to saying that an open pipe can respond to a series of notes whose vibration numbers have the ratios 1, 2, 3, 4, 5, etc. Hence we infer that it ought to be possible to cause both open and closed pipes to emit notes of higher pitch than their fundamentals (that is, overtones), and that the first overtone of an *open* pipe should have twice the rate of vibration of the fundamental (that is, it should be *do'*, the fundamental being considered as *do*); that the second overtone should vibrate three times as fast as the fundamental (that is, it should be *sol'*); that the third overtone should vibrate four times as fast (that is, it should be *do''*); that the fourth overtone should vibrate five times as fast (that is, it should be *mi''*); etc. In the case of the *closed* pipe, however, the first overtone should have a vibration rate three times that of the fundamental (that is, it should be *sol'*); the second overtone should vibrate five times as fast (that is, it should be *mi''*); etc. In other words, while an open pipe ought to give forth *all* the harmonics, both odd and even, a closed pipe ought to produce the *odd* harmonics but be entirely incapable of producing the *even* ones.

Let the pipe of Fig. 371 be blown so as to produce the fundamental when the lower end is open. Then let the strength of the air blast be increased. The note will be found to spring to *do'*. By blowing still harder it will spring to *sol'*, and a still further increase will probably bring out *do''*. The odd and the even harmonics are, in fact, emitted by the open pipe, as our theory predicted. When the lower end is closed, however, the first overtone will be found to be *sol'* and the next one *mi''*, just as our theory demands for the closed pipe.

413. Mechanism of emission of notes by pipes. Blowing across the mouth of a pipe produces a musical note, because the jet of air vibrates back and forth across the lip in a period which is determined wholly by the natural resonance period of the pipe. Thus, suppose that the jet *a* (Fig. 372) first strikes just inside the edge, or *lip*, of the pipe. A condensational pulse starts down the pipe. When it returns to the mouth after reflection at the closed end, it pushes the jet outside the lip. This starts a rarefaction down the pipe, which, after return from the lower end, pulls the jet in again. There are thus sent out into the room regularly timed puffs, the period of which is controlled by the reflected pulses coming back from the lower end, that is, by the natural resonance period of the pipe.

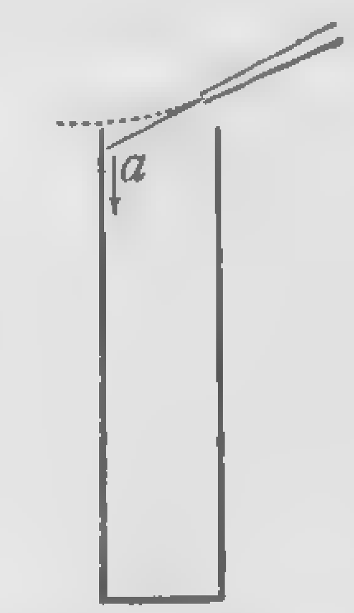


Fig. 372. Vibrating air jet

By blowing more violently it is possible to create, by virtue of the friction of the walls, so great and so sudden a compression in the mouth of the pipe that the jet is forced out over the edge before the return of the first reflected pulse. In this case no note will be produced unless the blowing is of just the right intensity to cause the jet to swing out in the period corresponding to an overtone. In this case the reflected pulses will return from the end at just the right intervals to keep the jet swinging in this period. This shows why a current of a particular intensity is required to start any particular overtone.

Another way of looking at the matter is to think of the pipe as being filled up with air until the pressure within it is great enough to force the jet outside the lip, upon which a period of discharge follows, to be succeeded in turn by another period of charge. These periods are controlled by the length of the pipe and the violence of the blowing, precisely as described above.

With open pipes the situation is in no way different except that the reflection of a condensation as a rarefaction at the lower end makes the natural period twice as high, since the pipe length is now one-half wave length instead of one-fourth wave length (see § 393).

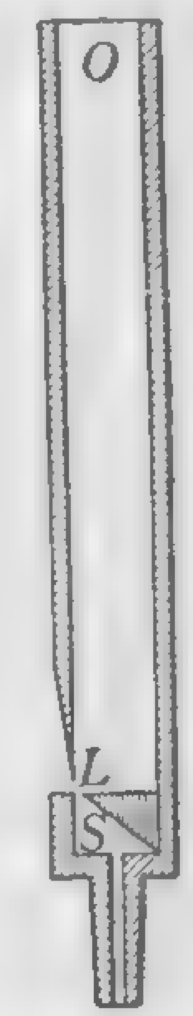


FIG. 373. Organ pipe

414. Vibrating-air-jet instruments. The mechanism of the production of musical tones by the ordinary organ pipe, the flute, the fife, the piccolo, and all whistles is essentially the same as in the case of the pipe of Fig. 372. In all these instruments an air jet is made to play across the edge of an opening in an air chamber, and the reflected pulses returning from the other end of the chamber cause it to vibrate back and forth, first into the chamber and then out again. In this way a series of regularly timed puffs of air is made to pass from the instrument to the ear of the observer precisely as in the case of the rotating disk of § 386. The air chamber may be either open or closed at the remote end. In the flute it is open, in whistles it is usually closed, and in organ pipes it may be either open or closed. Fig. 373 shows a cross section of an organ pipe. The jet of air from S vibrates across the lip L, in obedience to the pressure exerted on it by waves reflected from O. Pipe organs are provided with a different pipe for each note, but the flute, piccolo, and fife are made to produce a whole series of notes, either by blowing overtones or by opening holes in the tube, — an operation which is equivalent to cutting the tube off at the hole.

415. Vibrating-reed instruments. In reed instruments the vibrating air jet is replaced by a vibrating reed, or tongue, which opens and closes, at absolutely regular intervals, an opening against which the performer is directing a current of air. In the

clarinet, the oboe, the bassoon, etc. the reed is placed at the upper end of the tube (see l, Fig. 374), and the theory of its opening and closing the orifice so as to admit successive puffs of air to the pipe

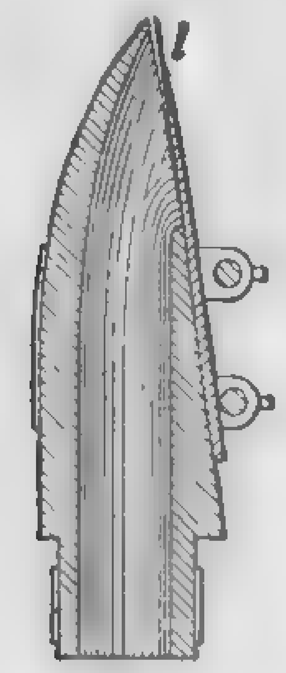


FIG. 374. Mouthpiece of a clarinet, showing the tongue l, which opens and closes the upper end of the pipe

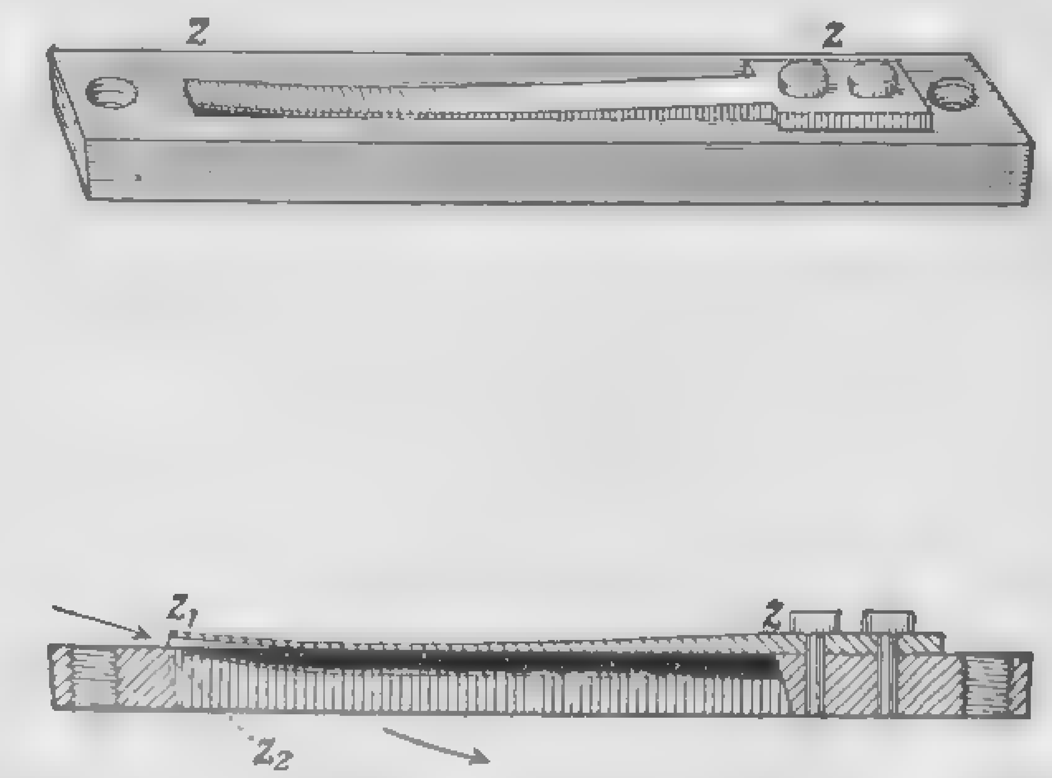


FIG. 375. The vibrating tongue of the mouth organ, accordion, etc.

is identical with the theory of the fluctuation of the air jet into and out of the organ pipe. For in these instruments the reed has little rigidity and its vibrations are controlled largely by the reflected pulses but partly by the reed and by the lips of the performer.

In other reed instruments, like the mouth organ, the common reed organ, or the accordion, it is the elasticity of the reed alone (see z, Fig. 375) which controls the emission of pulses. In such instruments there is no necessity for air chambers. The arrows of Fig. 375 indicate the direction of the air current which is interrupted as the reed vibrates between the positions z_1 and z_2.

In still other reed instruments, like the reed pipes used in large organs (Fig. 376), the period of the pulses is controlled partly by the elasticity of the reed and partly by the return of the reflected waves; in other words, the natural period of the reed is more or less coerced by the period of the reflected pulses. Within certain limits, therefore, such instruments may be tuned by merely changing the length of the vibrating reed l. This is done by pushing the wire r up or down.

FIG. 376. The reed-organ pipe

416. Vibrating-lip instruments. In instruments of the bugle and cornet type the vibrating reed is replaced by the vibrating lips of the musician, the period of their vibration being controlled, precisely as in the organ pipe or the clarinet, by the period of the returning pulses. In the bugle the pipe length is fixed, the instrument being without keys, and because of the narrowness of the tube all bugle calls are played with overtones.

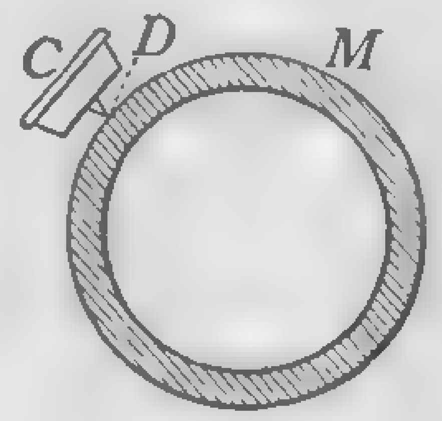


FIG. 377

417. The phonograph. In the original form of the phonograph the sound waves, collected by the cone, are carried to a thin metallic disk *C* (Fig. 377), exactly like a telephone diaphragm, which takes up very nearly the vibration form of the wave which strikes it. This vibration form is permanently impressed on the wax-coated cylinder *M* by means of a stylus *D* which is attached to the back of the disk. When the stylus is run a second time over the groove which it first made in the wax, it receives again and imparts to the disk the vibration form which first fell upon it. This is the principle of the dictaphone and the ediphone, used to replace stenographers in business offices. The typist writes the letter by listening to the reproduction of the dictation. The latest form of reproducer is illustrated opposite page 383.

SUMMARY. The fundamental of a closed pipe has a wave length four times as long as the pipe; that of an open pipe has a wave length twice as long as the pipe.

An open pipe has both odd and even harmonics, whereas a closed pipe has odd harmonics only.

QUESTIONS AND PROBLEMS*

1. An open organ pipe is 3.5 ft. long. What is the frequency of its fundamental tone if the speed of sound is 1120 ft. per second?

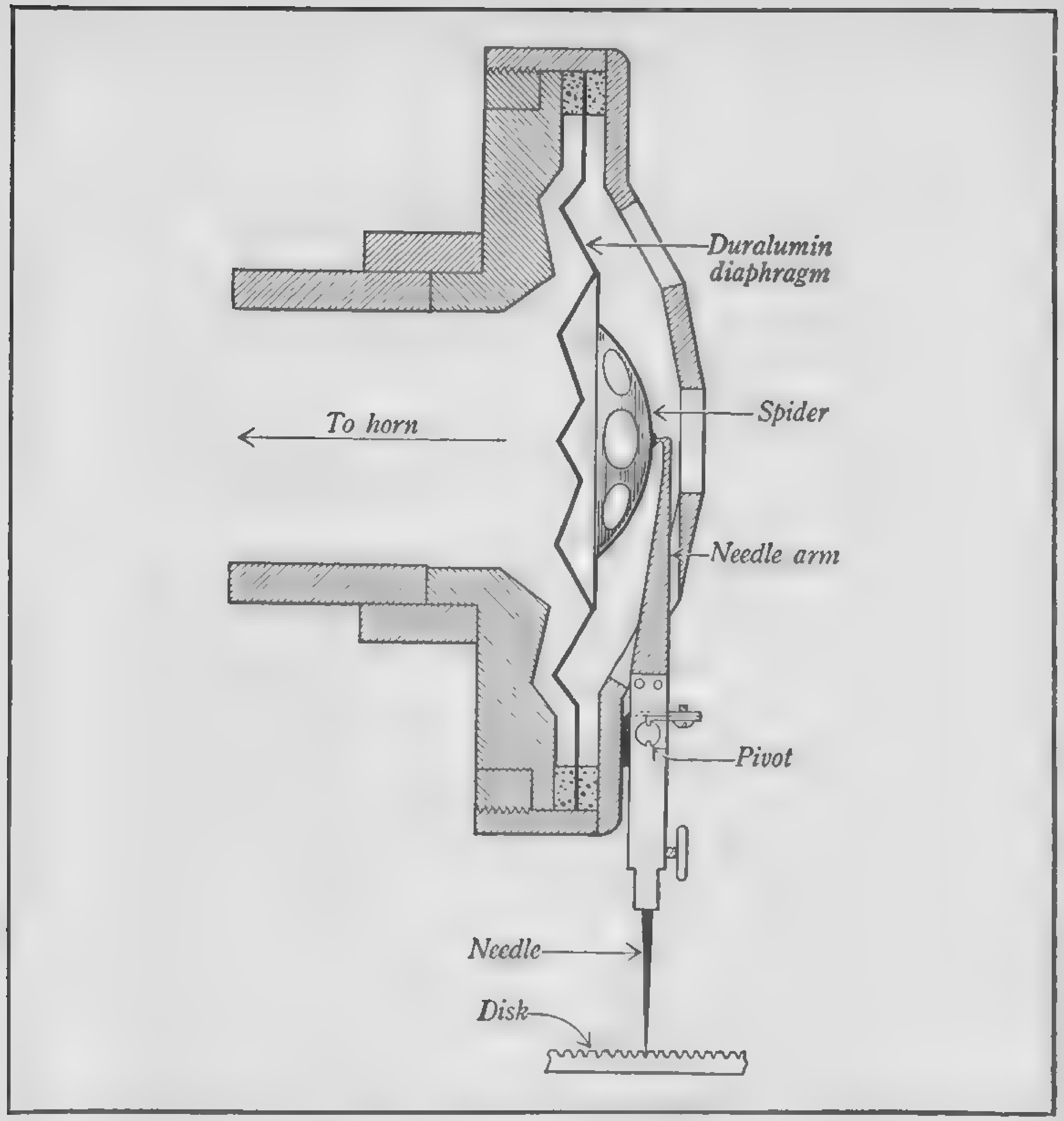
2. The ceiling of a small chapel was found to be too low to permit installing the 16-foot open pipe of the organ. How could the pipe have been altered for installation without changing its pitch?

3. Why is the quality of an open organ pipe different from that of a closed organ pipe?

* Supplementary questions and problems for Chapter XVII are given in the Appendix.

THOMAS A. EDISON (1847–1931)

The greatest and most prolific of all inventors; invented the phonograph, the high-resistance carbon-filament lamp, quadruplex telegraphy, and scores of other things



A PHONOGRAPH REPRODUCER

The peculiar form of diaphragm shown was designed to eliminate all natural frequencies characteristic of the diaphragm and hence to yield as distortionless reproduction as possible of the received wave form. The original wave form to be recorded falls upon the disk of a microphone precisely like those used in broadcasting and equally carefully designed to avoid distortion. The changes in the air pressure impressed upon this diaphragm are transformed by the microphone into current variations and these currents after amplification by distortionless vacuum-tube amplifiers operate magnetically the recording needle, similar to the one shown in the figure, which writes its wavy trace in soft wax. From this record in the wax a copper electrotype is made, and the wavy trace is then transferred from the copper plate by a hydraulic force of from five to ten tons applied to the commercial disks when they are hot enough to receive the impression. The figure shows how the needle of the reproducer follows the wavy trace and in turn impresses the original wave form upon the air in contact with the diaphragm

4. Explain how an instrument like the bugle, which has an air column of unchanging length, may be made to produce several notes of different pitch, as C, G, C', E', G'. (C is seldom used.)

5. What will be the relative lengths of a series of organ pipes which produce the eight notes of a diatonic scale?

6. The velocity of sound in hydrogen is about four times as great as it is in air. If a C pipe is blown with hydrogen, what will be the pitch of the note emitted?

7. Why is the pitch of a sound emitted by a phonograph raised by increasing the speed of rotation of the disk?

8. In making a lateral-cut phonograph record, what visible effect will be produced on the disk if the loudness of the note is increased? if the pitch is lowered an octave?

9. Mention two musical instruments, the first of which depends upon resonance and the second upon forced vibrations for sound intensification.

10. What proves that a musical note is transmitted as a wave motion?

11. What evidence have you that sound waves are longitudinal vibrations?

12. Explain the mechanism of production of musical sounds in each of the instruments shown opposite page 373.

CHAPTER XVIII

NATURE AND PROPAGATION OF LIGHT

Transmission of Light

418. Speed of light. Before the year 1675 light was thought to pass instantaneously from the source to the observer. In that year, however, Olaus Römer, a young Danish astronomer, made the following observations. He had observed accurately the instant at which a satellite of Jupiter, *M* (Fig. 378), passed into Jupiter's shadow when the earth was at *E*, and he forecast, from the known mean time between such eclipses, the exact instant at which a given eclipse ought to occur six months later, when the earth should be at *E′*. It actually took place 16 minutes 36 seconds (or 996 seconds) later. Römer concluded that the 996 seconds' delay represented the time required for light to travel across the earth's orbit, a distance known to be about 180,000,000 miles. The most precise of modern determinations of the speed of light are made by laboratory methods. The generally accepted value, that of Michelson, of The University of Chicago, is 299,800 kilometers per second. It is sufficiently correct to remember it as 300,000 kilometers, or 186,000 miles. Though this speed

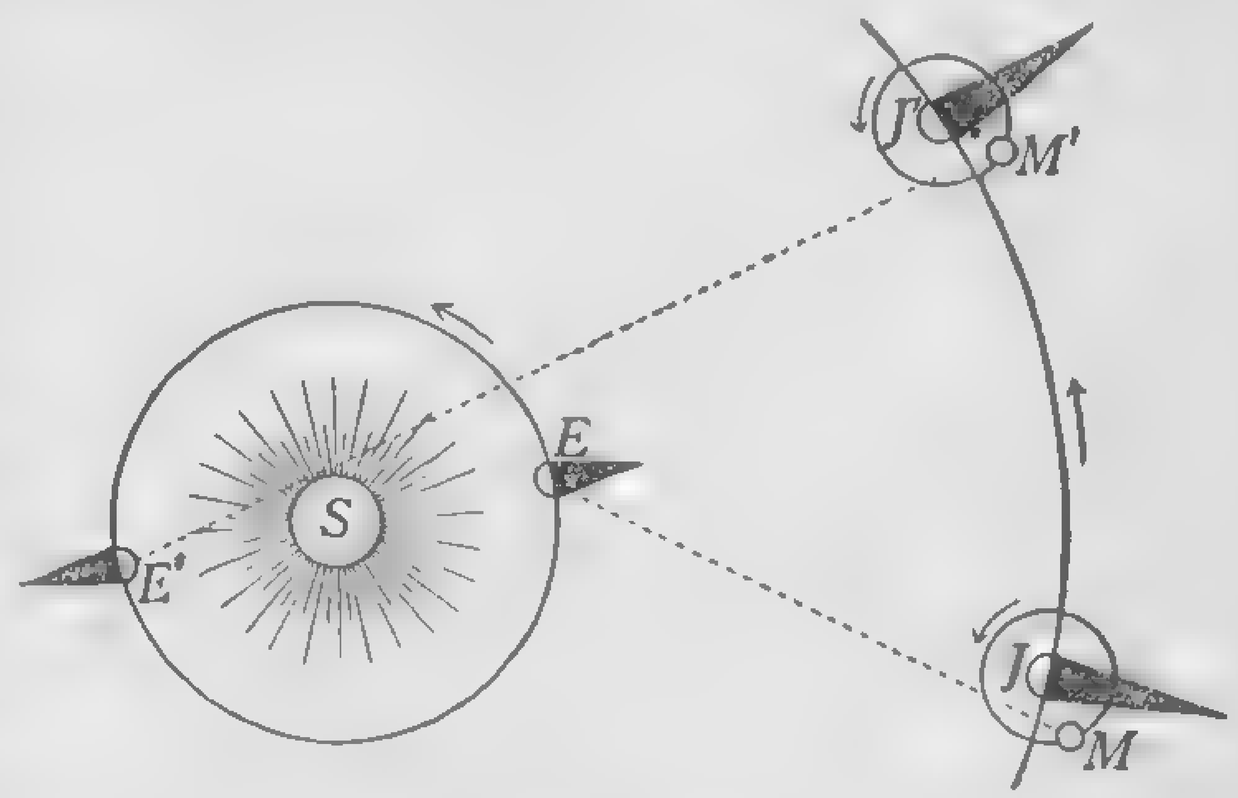


Fig. 378. Illustrating Römer's determination of the velocity of light

would carry light around the earth $7\frac{1}{2}$ times in a second, yet it is so small in comparison with interstellar distances that the light which is now reaching the earth from the nearest fixed star, Alpha Centauri, started 4.3 years ago. If an observer on the pole star had a telescope powerful enough to enable him to see events on the earth, he would not have seen the battle of Gettysburg (which occurred in July, 1863) until January, 1918. The distances of some of the spiral nebulæ have recently been measured by E. P. Hubble of the Mt. Wilson Observatory, who finds them to be so astoundingly remote from us that the light by which we now see these nebulæ started about one million years ago.

Both Foucault in France and Michelson in America have measured directly the velocity of light in water and have found it to be only three fourths as great as in air. It will be shown later that in all transparent liquids and solids it is less than it is in air.

419. Reflection of light.* Let a beam of sunlight be admitted to a darkened room through a narrow slit. The straight path of the beam will be rendered visible by the brightly illumined dust particles suspended in the air. Let the beam fall on the surface of a mirror. Its direction will be seen to be sharply changed, as shown in Fig. 379. Let the mirror be held so that it is perpendicular to the beam. The beam will be seen to be reflected directly back on itself. Let the mirror be turned through an angle of 45°. The reflected beam will move through 90°.

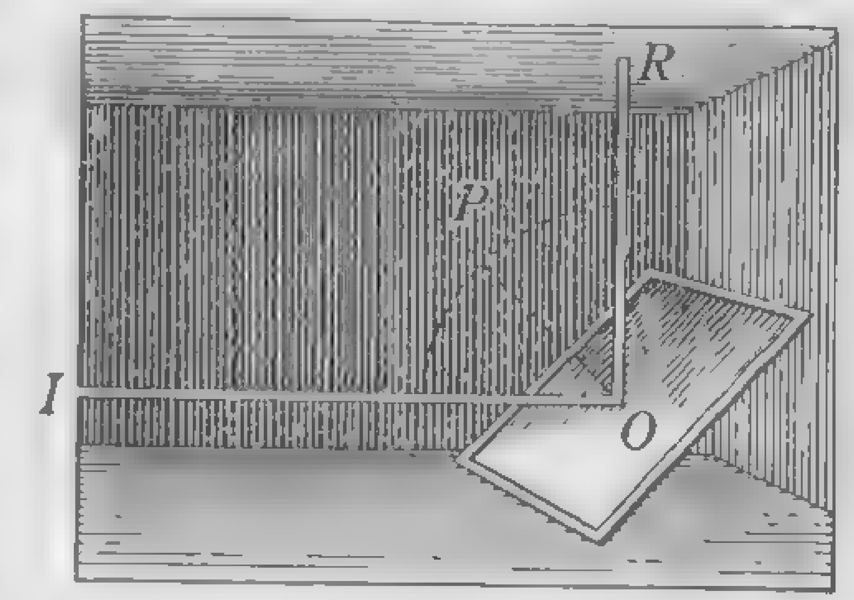


Fig. 379. Illustrating law of reflection of light

The experiment shows roughly, therefore, that the angle *IOP*, between the incident beam and the normal to the mirror, is equal to the angle *POR*, between the reflected beam and the normal to the mirror. The first angle, *IOP*, is called

* An exact laboratory experiment on the law of reflection should either precede or follow this discussion. See, for example, Experiment 54 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

the angle of incidence, and the second, *POR*, the angle of reflection. *The angle of reflection is equal to the angle of incidence.*

420. Diffusion of light. In the last experiment the light was reflected by a very smooth plane surface. Now let the beam be allowed to fall upon a rough surface like that of a sheet of unglazed white paper. No reflected beam will be seen; but instead the whole room will be brightened appreciably, so that the outline of objects before invisible may be plainly distinguished.

The beam has evidently been scattered in all directions by the innumerable little reflecting surfaces of which the surface of the paper is composed. The effect will be much more noticeable if the beam is allowed to fall alternately on a piece of dead-black cloth and on the white paper. The light is largely absorbed by the cloth, whereas it is scattered or *diffusely reflected* by the paper. Illumination sufficiently strong for sewing on white material may be altogether too weak for working on black goods. The difference between a smooth reflector and a rough one is illustrated in greatly magnified form in Fig. 380. The air shafts of apartment houses are made white to get the maximum diffusion of daylight into rooms that might otherwise be very dark.

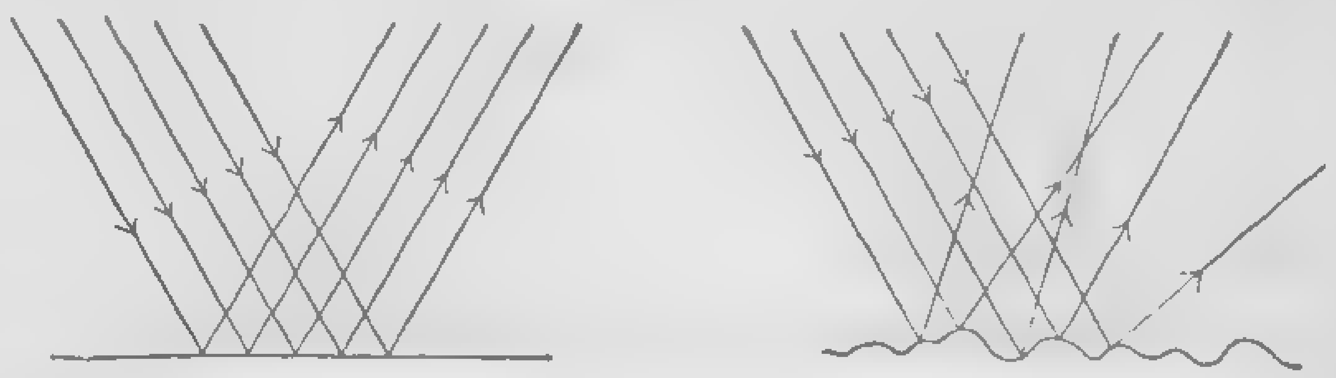


FIG. 380. Regular and irregular reflection

421. Visibility of nonluminous bodies. Everyone is familiar with the fact that certain classes of bodies, such as the sun, a gas flame, etc., are self-luminous (visible on their own account), whereas other bodies, like books, chairs, tables, etc., can be seen only when they are in the presence of luminous bodies. The above experiment shows how such nonluminous, diffusing bodies become visible in the presence of luminous bodies. For, since a diffusing surface scatters in all directions the light which falls upon it, each small element of such a surface is sending out light in a great many directions, in much the

same way in which each point on a luminous surface is sending out light in all directions. Hence we always see the *outline* of a diffusing surface as we do that of an emitting surface, no matter where the eye is placed. On the other hand, when light comes to the eye from a polished reflecting surface, since the form of the beam is wholly undisturbed by the reflection, we see the outline not of the mirror but rather of the source from which the light came to the mirror, whether this source is itself self-luminous or not. All bodies other than self-luminous ones are visible only by the light which they diffuse. Black bodies send no light to the eye, but their outlines can be distinguished by the light which comes from the background. Any object *which can be seen*, therefore, may be regarded as itself sending rays to the eye; that is, it may be treated as a luminous body.

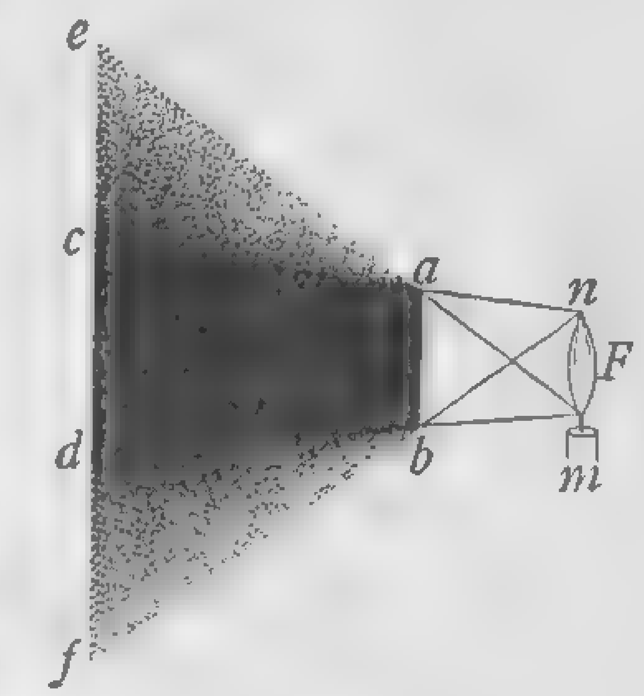


FIG. 381. Shadow from a broad source

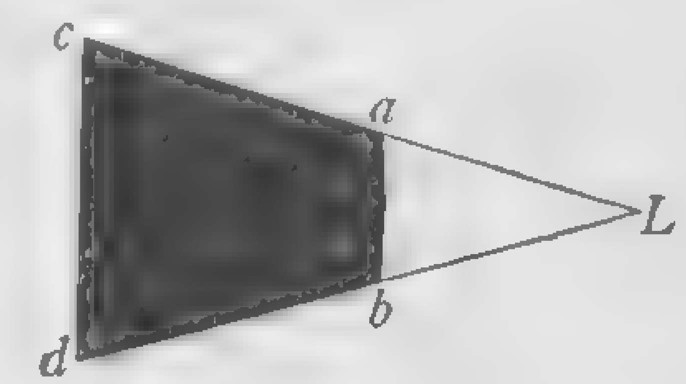


FIG. 382. Shadow from a small source

422. Shadows. Let any opaque object be held very close to a white screen placed opposite a window or a broad gas flame. So long as the object is very close to the screen the shadow is uniformly dark, but as it is moved toward the source of light (*F*, Fig. 381) two parts to the shadow will be observed: a very black part, *cd*, in the middle, from which all the light from the source is excluded; and a part, *ec* and *df*, which grows gradually lighter with distance from the dark center *cd*.

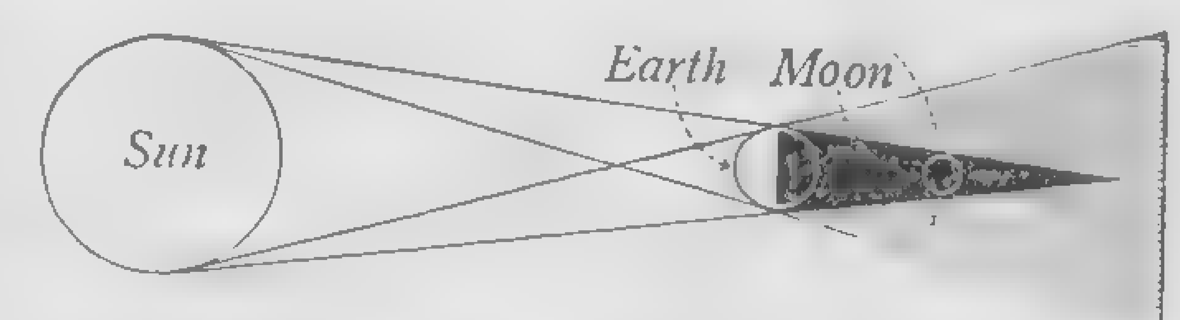


FIG. 383. Illustrating a total eclipse of the moon by passage into the umbra of the earth

These effects are easily explained on the basis of the rectilinear propagation of light. The region *abdc*, from which the

light from all points of the source *mn* is excluded, is called the *umbra*. The region *ace* and *bdf*, which receives light from some portions of the source but not from all, is called the *penumbra*. It will be seen from the figure that the *penumbra* must decrease as the object approaches the screen, and also as the size of the source diminishes. When the source becomes a mere point there is no penumbra at all (Fig. 382). When the source is larger than the opaque object, as in the case of the sun and earth, the umbra is a cone, as shown in Fig. 383.

SUMMARY. The velocity of light is 300,000 kilometers per second, or 186,000 miles per second.

The angle of reflection equals the angle of incidence.

Diffusion of light is its irregular reflection.

Nonluminous bodies are seen by the light which they diffuse. A perfect reflector would be invisible.

QUESTIONS AND PROBLEMS

1. Sirius, the brightest star, is about 52,000,000,000,000 miles away. If it were suddenly annihilated, how long would it shine on for us?

2. Devise an arrangement of mirrors by means of which you could see over and beyond a high stone wall or trench embankment. This is a very simple form of periscope.

3. Why is a room with white walls much lighter than a similar room with black walls?

4. Compare the reflection of light from white blotting paper with that from a plane mirror. Which of these objects is more easily detected from a distance? Why?

5. Show by a diagram the relative positions of the earth, the sun, and the moon during a total eclipse of the moon, indicating by lines the umbra of the earth and by a dot the position of the observer.

6. Explain a total eclipse of the sun by the method used in question 5. Explain similarly a partial eclipse of the sun.

7. Will it ever be possible for the moon totally to eclipse the sun from the whole of the earth's surface at once?

ILLUMINATION AND PHOTOMETRY

WED

423. Intensity of illumination. Let four candles be set as close together as possible in such a position *B* as to cast upon a white screen *C*, placed in a well-darkened room, a shadow of an opaque object *O* (Fig. 384). Let one single candle be placed in such a position *A* as to cast another shadow of *O* upon the screen. Since light from *A* falls on the shadow cast by *B*, and light from *B* falls on the shadow cast by *A*, it is clear that the two shadows will appear equally dark only when light of equal intensity falls on each; that is, when *A* and *B* produce equal illumination upon the screen. Let the positions of *A* and *B* be shifted until this condition is fulfilled. Then let the distances from *B* to *C* and from *A* to *C* be measured. If all five candles are burning with flames of the same size, the first distance will be found to be just twice as great as the second. Hence the illumination produced upon the screen by each one of the candles at *B* is but one fourth as great as that produced on the screen by one candle at *A*, one half as far away.

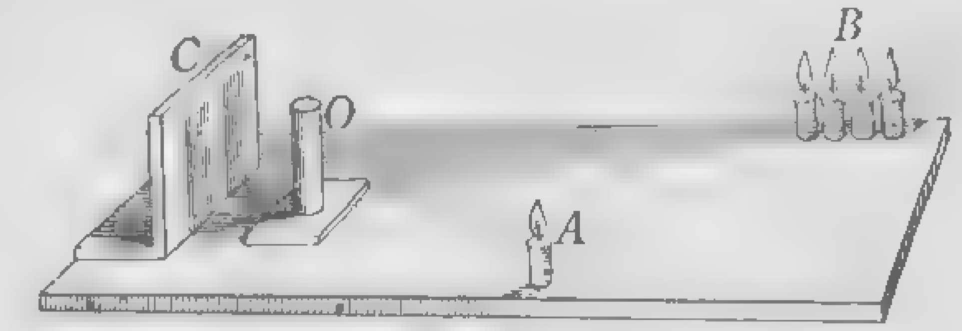


FIG. 384. Rumford's photometer

The above is the direct experimental proof that *the intensity of illumination varies inversely as the square of the distance from the source.*

The theoretical proof of the law is furnished at once by Fig. 385, for since all the light which falls from the candle *L*

FIG. 385. Proof of law of inverse squares

on *A* is spread over four times as large an area when it reaches *B*, twice as far away, and over nine times as large an area when it reaches *C*, three times as far away, obviously the *intensities* at *B* and at *C* can be but one fourth and one ninth as great as at *A*.

This method of comparing experimentally the intensities of two lights was first used by Count Rumford. The arrangement is therefore called the *Rumford photometer* (light measurer).

424. Candle power and foot candle. The last experiment furnishes a method of comparing the *light-emitting powers* of various sources of light. For example, suppose that the four candles at B are replaced by a gas flame, and that for the condition of equal illumination upon the screen the two distances BC and AC are the same as those given above, namely, 2 to 1. We should then know that the gas flame, which is able to produce the same illumination at a distance of two feet as a candle at a distance of one foot, has a light-emitting power equal to four candles. In general, then, *the candle powers of any two sources which produce equal illumination on a given screen are directly proportional to the squares of the distances of the sources from the screen.*

It is customary to express the intensities of all sources of light in terms of candle power, one candle power being defined as the amount of light emitted by a sperm candle $\frac{7}{8}$ inch in diameter and burning 120 grains (7.776 grams) per hour. The candle power of an ordinary gas flame burning 5 cubic feet per hour is from 16 to 25, depending on the quality of the gas.

A standard candle at a distance of 1 foot gives an intensity of illumination called a *foot candle.* A 100-candle-power lamp, for example, at a distance of 1 foot gives an intensity of illumination of 100 foot candles; at 2 feet, of 25 foot candles; at 5 feet, of 4 foot candles; and at 10 feet, of 1 foot candle. In general, foot candles = candle power/feet^2. In ordinary rooms we experience no such falling off in intensity of illumination because of diffusion of light by the walls. (The foot-candle meter is described opposite page 391.)

425. Bunsen's photometer. Let a drop of oil or melted paraffin be placed in the middle of a sheet of unglazed white paper to render it translucent. Let the paper be held near a window and the

A. A. MICHELSON, CHICAGO

Distinguished for his extraordinarily accurate experimental researches in light. First American scientist to receive the Nobel prize

LORD RAYLEIGH (ENGLAND)

Distinguished for the discovery of argon, for very accurate determinations in electricity and sound and for profound theoretical studies

HENRY A. ROWLAND, JOHNS HOPKINS

Distinguished for the invention of the concave grating and for epoch-making studies in heat and electricity

SIR WILLIAM CROOKES, LONDON

Distinguished for his pioneer work (1875) in the study and interpretation of cathode rays (pp. 470 and 477)

A GROUP OF MODERN PHYSICISTS

THE FOOT-CANDLE METER

The foot-candle meter makes use of a series of highly translucent spots located at increasing distances from a small incandescent lamp placed inside a dark box near one end of the series of spots. The spots are therefore illuminated by the small working standard with intensities that diminish with distance from the lamp. When the meter is placed to receive light from an external source, all the spots receive the same intensity of illumination from without. That particular spot which is equally illuminated on both sides becomes invisible, thus indicating the intensity of illumination of the outside source in foot candles

side *away from* the window observed. The oiled spot will appear *lighter* than the remainder of the paper. Then let the paper be held so that the side nearest the window may be seen. The oiled spot will appear *darker* than the rest of the paper. We learn, therefore, that *when the paper is viewed from the side of greater illumination, the oiled spot appears dark*; but *when it is viewed from the side of lesser illumination, the spot appears light.* If, then, the two sides of the paper are equally illuminated, the spot ought to be of the same brightness when viewed from either side. Let the room be darkened and the oiled paper placed between two gas flames, two electric lights, or any two equal sources of light. It will be observed that when the paper is held closer to one than the other, the spot will appear dark when viewed from the side next the closer light; but if it is then moved until it is nearer the other source, the spot will change from dark to light when viewed always from the same side. It is always possible to find some position for the oiled paper at which the spot either disappears altogether or at least appears the same when viewed from either side. This is the position at which the illuminations from the two sources are equal. Hence, to find the candle power of any unknown source it is only necessary to set up a candle on one side and the unknown source on the other, as in Fig. 386, and to move the spot A to the position of equal illumination. The candle power of the unknown source at C will then be the square of the distance from C to A, divided by the square of the distance from B to A.

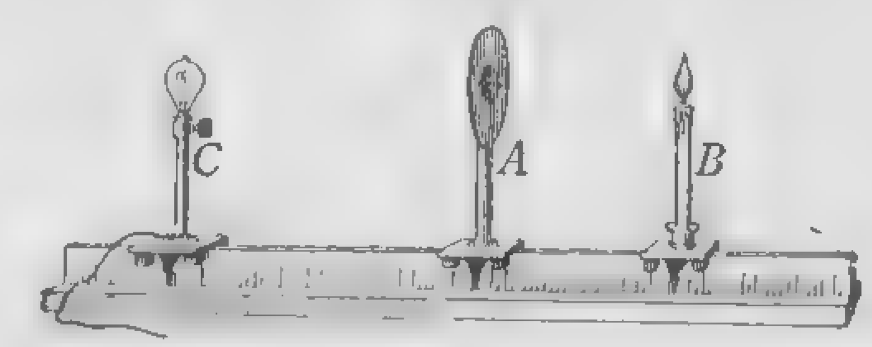


FIG. 386. Bunsen's photometer

This arrangement is known as the *Bunsen photometer.*

SUMMARY. The intensity of light varies inversely with the square of the distance from its source.

The candle powers of any two sources which produce equal illumination on a given screen are directly proportional to the squares of the distances of the sources from the screen.

A foot candle is the intensity of illumination of a candle-power light at a distance of one foot.

QUESTIONS AND PROBLEMS

1. Distinguish between intensity of a source of light and intensity of illumination. In what unit is each measured?

2. If the sun were at the distance of the moon from the earth, instead of at its present distance, how much stronger would sunlight be than at present? (The moon is 240,000 mi. and the sun 93,000,000 mi. from the earth.)

3. If 20 sec. is the proper length of exposure when you are printing photographs by a gas light 8 in. from the printing frame, what length of exposure would be required in printing from the same negative at a distance of 16 in. from the same light?

4. If a 20-second exposure is correct at a distance of 6 in. from an 8-candle-power electric light, what is the required time of exposure at a distance of 12 in. from a 32-candle-power electric light?

5. If 4 foot candles is the proper illumination for reading, how far from the page of a book should a 16-candle-power light be placed in order to give this illumination?

6. A standard candle furnishes the same intensity of light upon a screen 2 ft. distant as another source of light furnishes when at a distance of 8 ft. (1) What is the candle power of the second light? (2) How great is the intensity of illumination of the screen in foot candles when one of these lights shines upon it?

7. If a gas flame is 300 cm. from the screen of a Rumford photometer, and a standard candle 50 cm. away gives a shadow of equal intensity, what is the candle power of the gas flame?

8. Which has the greater luminous efficiency, a lamp rated at 1.3 watts per candle power, or one rated at 1.5 watts per candle power? Why?

THE WAVE THEORY OF LIGHT

426. The corpuscular theory of light. All the properties of light which have so far been discussed are perhaps most easily accounted for on the hypothesis that light consists of streams of very minute particles, or *corpuscles*, projected with the enormous velocity of 300,000 kilometers per second from all luminous bodies. The facts of straight-line propagation and reflection are exactly as we should expect them to be if this were the nature of light. The facts of refraction can also be accounted for, although somewhat less simply, on this hypothesis. As a matter of fact, this theory of the nature of light, known as the *corpuscular theory*, was the one most generally accepted up to about 1800.

427. The wave theory of light. A rival hypothesis, which was first completely formulated by the great Dutch physicist Huygens (1629–1695), regarded light, like sound, as a *form of wave motion.* This hypothesis met at the start with two very serious difficulties. In the first place, light, unlike sound, not only travels with perfect readiness through the best vacuum which can be obtained with an air pump, but it travels without any apparent difficulty through the great interstellar spaces which are probably infinitely better vacua than can be obtained by artificial means. If, therefore, light is a wave motion, it must be a wave motion of some medium which fills all space and yet does not hinder the motion of the stars and planets. Huygens assumed such a medium to exist, and called it the *ether*.

The second difficulty in the way of the wave theory of light was that it apparently failed to account for the fact of straight-line propagation. Sound waves, water waves, and all other forms of waves with which we are most familiar bend readily around corners, whereas light apparently does not. It was this difficulty chiefly which led many of the most famous of the early philosophers, including the great Sir Isaac Newton, to reject the wave theory and to support the projected-particle theory. Within the last hundred years, however, this difficulty has been completely removed, and in addition other properties of light have been discovered for which the wave theory offers the only satisfactory explanation. The most important of these properties will be treated in the next paragraph.

428. Interference of light. Let two pieces of plate glass about $\frac{1}{2}$ inch wide and 4 or 5 inches long be separated at one end by a thin sheet of paper in the manner shown in Fig. 387, and

the other end clamped or held firmly together, so that a very thin wedge of air exists between the plates. Let a piece of asbestos or blotting paper be soaked in a solution of common salt (sodium chloride) and placed over the tube of a Bunsen burner so as to touch the flame in the manner shown. The flame will be colored a bright yellow by the sodium in the salt. When the eye looks at the reflection of the flame from the glass surfaces, a series of fine black and yellow lines will be seen to cross the plate.

The wave theory offers the following explanation of these effects. Each point of the flame sends out light waves which travel to the glass plate and are in part reflected and in part transmitted at all the surfaces of the glass, that is, at $A'B'$, at AB, at CD, and at $C'D'$ (Fig. 387). We will consider, however, only those reflections which take place at the two faces of the air wedge, namely, at AB and CD. Let Fig. 388 represent a greatly magnified section of these two surfaces. Let the wavy line as represent a light wave reflected from the surface AB at the point a, and returning thence to the eye. Let the dotted wavy line ir represent a light wave reflected from the surface CD at the point i, and returning thence to the eye. Similarly, let all the continuous wavy lines of the figure represent light waves reflected from different points on AB to the eye, and let all the dotted wavy lines represent waves reflected from corresponding points on CD to the eye. Now, in precisely the same way in which two trains of sound waves from two tuning forks were found, in the experiment illustrating beats (see § 396), to interfere with each other so as to produce silence whenever the two waves corresponded to motions of the air particles in opposite directions, so in this experiment the two sets of light waves from AB and CD inter-

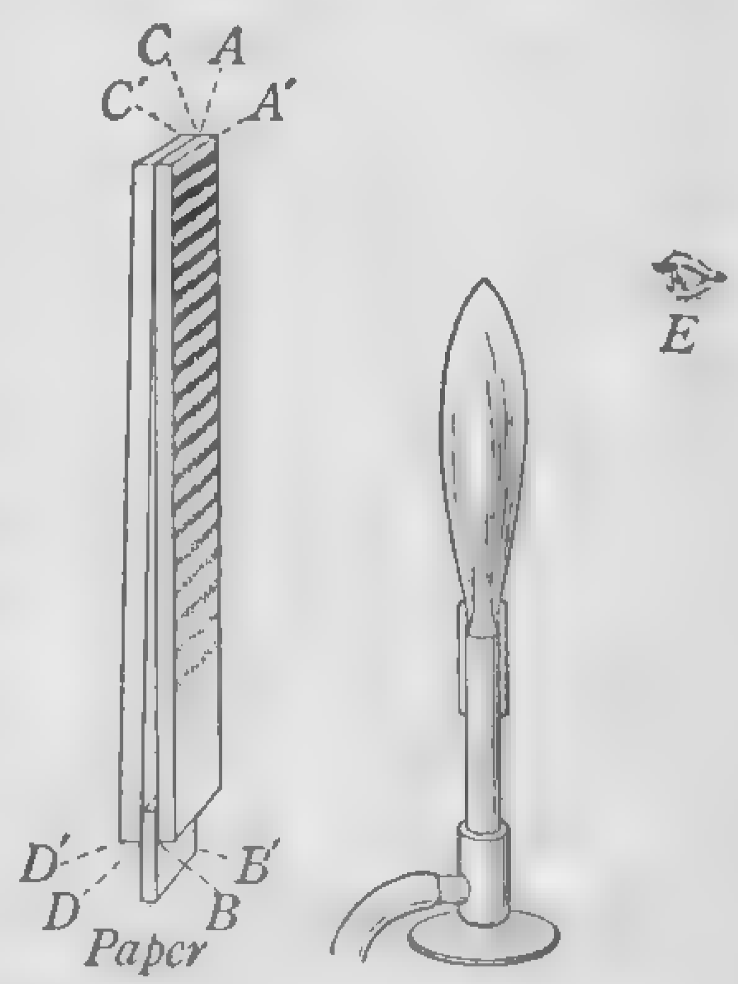


FIG. 387. Interference of light waves

fere with each other so as to produce darkness wherever these two waves correspond to motions of the light-transmitting medium in opposite directions. The dark bands, then, of our experiment are simply the places at which the two beams reflected from the two surfaces of the air film neutralize or destroy each other, whereas the light bands correspond to the places at which the two beams reënforce each other and thus produce illumination of double intensity. The position of the second dark band c must of course be determined by the fact that the distance from c to k and back (see Fig. 388) is a wave length more than from a to i and back, and so on down the wedge. This phenomenon of the interference of light is met with in many different forms, and in every case the wave theory furnishes at once a wholly satisfactory explanation of the observed effects. The corpuscular theory, on the other hand, is unable to account for any of these interference effects. Hence the corpuscular theory in its original form is now practically abandoned. However, some new phenomena called *photoelectric effects* have recently been discovered which find simpler interpretation in some modified form of the corpuscular theory than in the wave theory. But, for the understanding and remembering of the most familiar properties of light it is still necessary, and probably will always continue to be necessary, to think in terms of waves. Indeed, we know definitely that light

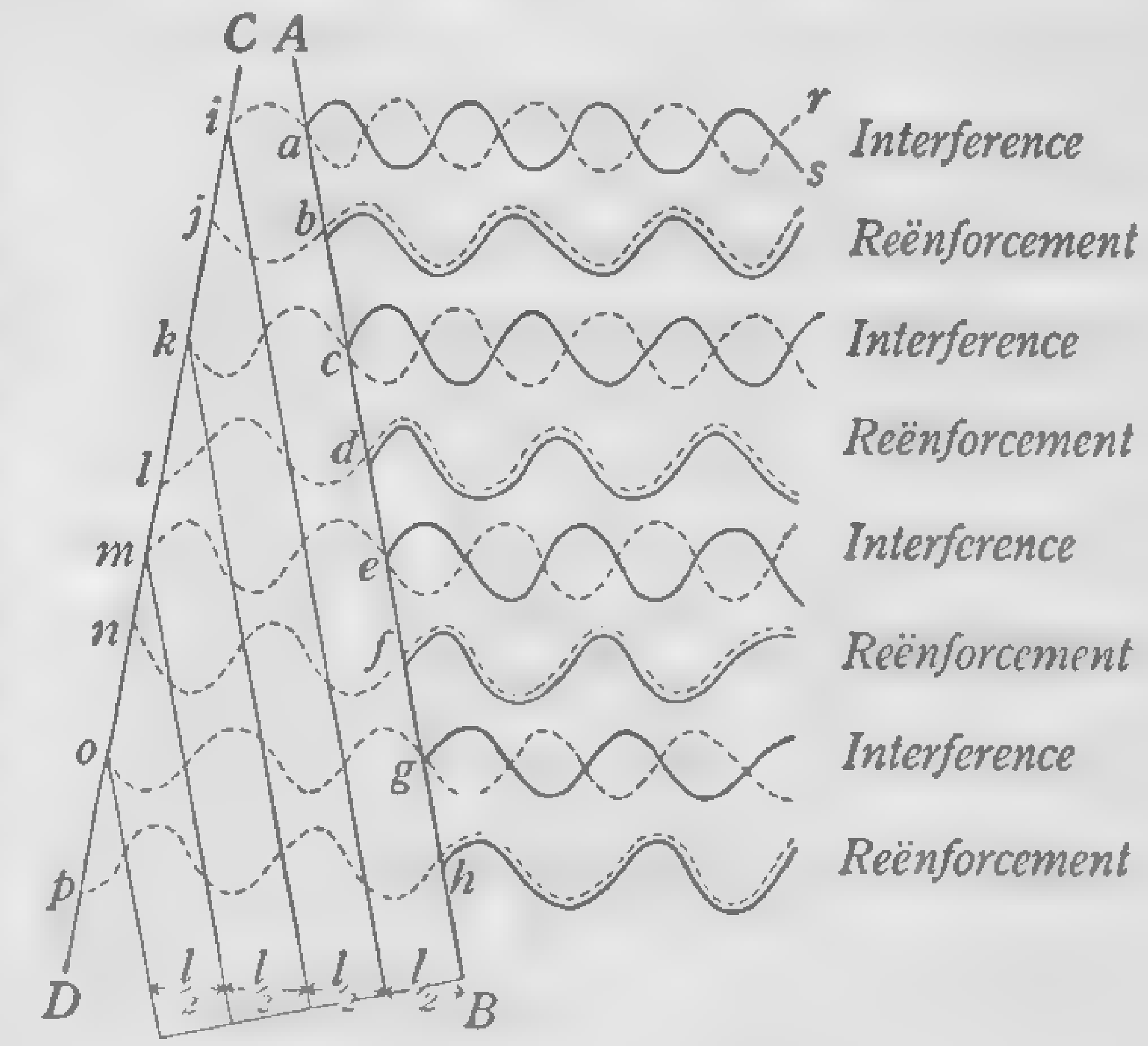


FIG. 388. Explanation of formation of dark and light bands by interference of light waves

waves are just like wireless waves except that they are of very much shorter wave length.

429. The ether. We have already indicated that if the wave theory is to be used, we must conceive, with Huygens, that all space is filled with a wave-transmitting medium. This medium cannot be like any of the ordinary forms of matter; for if any of these forms existed in interplanetary space, the planets and the other heavenly bodies would certainly be retarded in their motions. As a matter of fact, in all the hundreds of years during which astronomers have been making accurate observations of the motions of heavenly bodies no such retardation has ever been observed. The medium which transmits light waves must therefore have a density which is infinitely small even in comparison with that of our lightest gases.

Further, in order to account for the transmission of light through transparent bodies, it is necessary to assume that the ether penetrates not only all interstellar spaces but all intermolecular spaces as well.

430. Wave length of yellow light. Although light, like sound, is a form of wave motion, light waves differ from sound waves in several important respects. In the first place, an analysis of the preceding experiment, which seems to establish so conclusively the correctness of the wave theory, shows that the wave length of light is extremely minute in comparison with that of ordinary sound waves. The wave length of the yellow light used in that experiment is .00006 centimeter (about $\frac{1}{40,000}$ inch).

The *number of vibrations per second* of light waves may be found, as in the case of sound, by dividing the velocity by the wave length. Since the velocity of light is 30,000,000,000 centimeters per second and the wave length is .00006 centimeter, the number of vibrations per second of yellow light has the enormous value 500,000,000,000,000.

431. Light waves transverse. Thus far we have discovered but two differences between light waves and sound waves; namely, the former are disturbances in the ether and always travel with the enormous speed of 186,000 miles per

second in a vacuum, whereas the latter are disturbances in ordinary matter and travel 1100 feet per second in air and a few times faster in liquids and solids. There exists, however, a further radical difference, which follows from a capital discovery made by Huygens (see opposite page 402) in the year 1690. It is this: While sound waves consist, as we have already seen, of *longitudinal* vibrations of the particles of the transmitting medium, that is, vibrations back and forth in the line of propagation of the wave, light waves are like the water waves of Fig. 352, p. 351, in that they consist of *transverse* vibrations, that is, vibrations of the medium at right angles to the direction of the line of propagation.

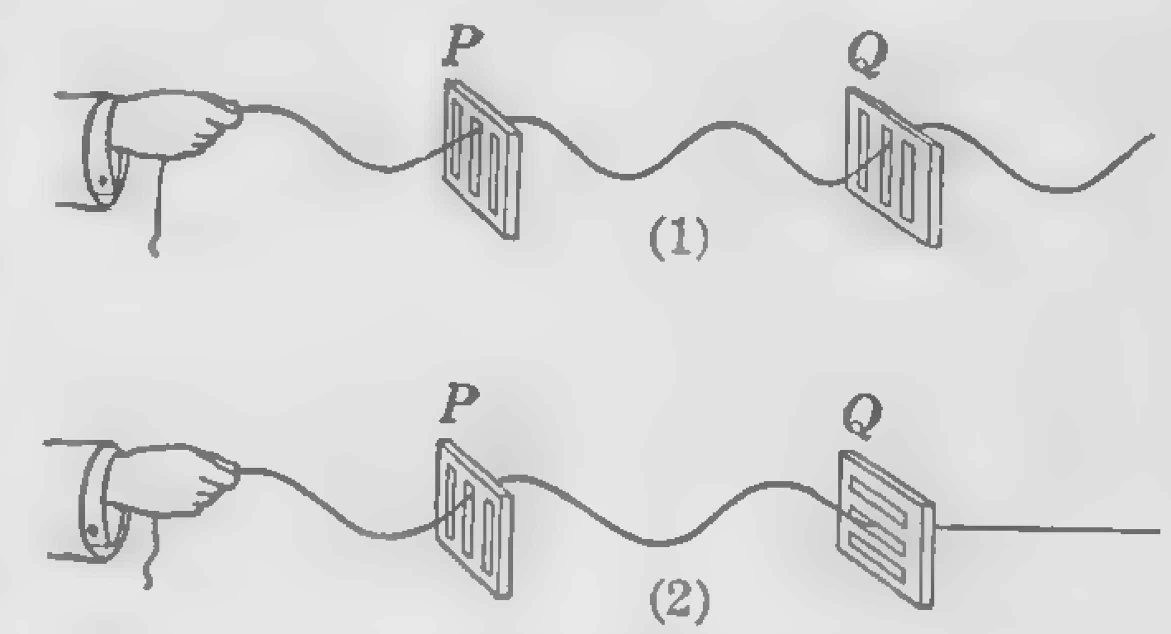


FIG. 389. Transverse waves passing through slits

In order to appreciate the difference between the behavior of waves of these two types under certain conditions, conceive of transverse waves in a rope being made to pass through two gratings in succession, as in Fig. 389. So long as the slits in both gratings are parallel to the plane of vibration of the hand, as in Fig. 389 (1), the waves can pass through them with perfect ease; but if the slits in the first grating P are parallel to the direction of vibration, and those of the second grating Q are turned at right angles to this direction, as in Fig. 389 (2), it is evident that the waves will pass readily through P, but will be stopped completely by Q, as shown in the figure. In other words, these gratings P and Q will let through only such vibrations as are parallel to the direction of their slits.

If, on the other hand, a longitudinal instead of a transverse wave — for example, a sound wave — had approached such a grating, it would have been as much transmitted in one

position of the grating as in another, since a *to-and-fro* motion of the medium can evidently pass through the slits with exactly the same ease, no matter how they are turned.

Now two crystals of tourmaline are found to behave with respect to light waves just as the two gratings behave with respect to the waves on the rope.

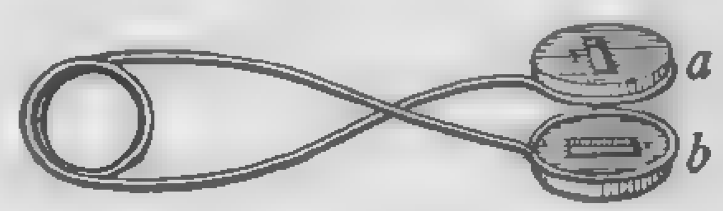


FIG. 390. Tourmaline tongs

Let one such crystal, *a* (Fig. 390), be held in front of a small hole in a screen through which a beam of sunlight is passing to a neighboring wall; or, if the sun is not shining, simply let the crystal be held between the eye and a source of light. The light will be readily transmitted, although somewhat diminished in intensity. Then let a second crystal, *b*, be held in line with the first. The light will still be transmitted, *provided the axes of the crystals are parallel,* as is shown in Fig. 391. When, however, one of the crystals is rotated in its ring through 90° (Fig. 392), the light is *cut off.* This shows that a crystal of tourmaline is capable of transmitting only light which is vibrating in one particular plane.

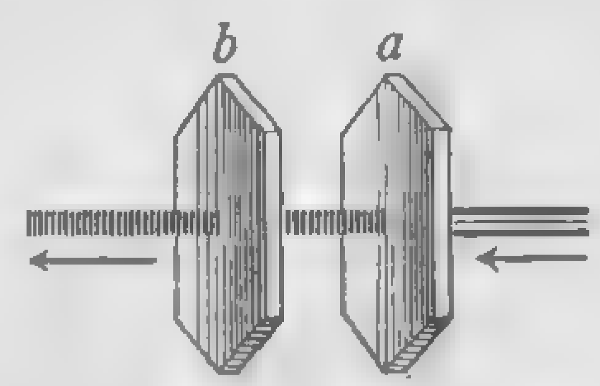


FIG. 391. Light passing through tourmaline crystals

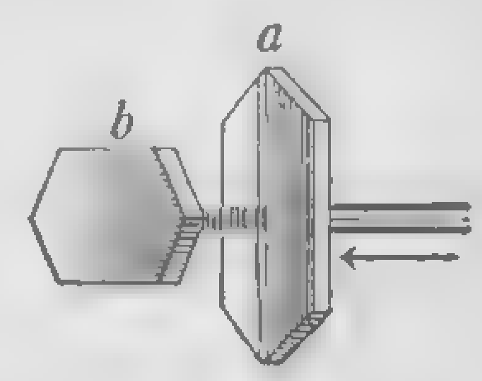


FIG. 392. Light cut off by crossed tourmaline crystals

From this experiment, therefore, we are forced to conclude that *light waves are transverse rather than longitudinal vibrations.* The experiment illustrates what is technically known as the *polarization of light,* and the beam which, after passage through *a*, is unable to pass through *b* if the axes of *a* and *b* are crossed, is known as a *polarized beam.* It is, then, the phenomenon of the *polarization of light* upon which we base the conclusion that light waves are transverse.

SUMMARY. Interference phenomena indicate that light is a wave motion.

Polarization phenomena indicate that light waves are transverse.

Oct 7

QUESTIONS AND PROBLEMS

1. Describe the strongest experimental evidence you know for the wave theory of light.

2. In what respect do light waves differ from sound waves?

3. Describe the experimental evidence for the theory of the transverse character of light waves.

4. If the waves of light from a certain green ribbon were .00005 cm. long, how many waves per second did it send into your eye?

REFRACTION OF LIGHT

432. Refraction. Let a narrow beam of sunlight be allowed to fall on a thick rectangular glass plate with a polished front and whitened back * (Fig. 393). It will be seen to split into a reflected and a transmitted portion. The transmitted portion will be seen to be bent toward the perpendicular OP drawn into the glass. Upon reaching the air it will again be seen to split into a reflected and transmitted portion, but the part passing into the air will this time be bent away from the perpendicular $O'P'$ drawn into the air. Let the incident beam strike the surface at different angles. It will be seen that *the greater the angle of incidence the greater the bending.* At normal incidence there will be no bending at all. If the upper and lower faces of the glass are parallel, the bending at the two faces will always be the same; consequently the emergent beam is parallel to the incident beam.

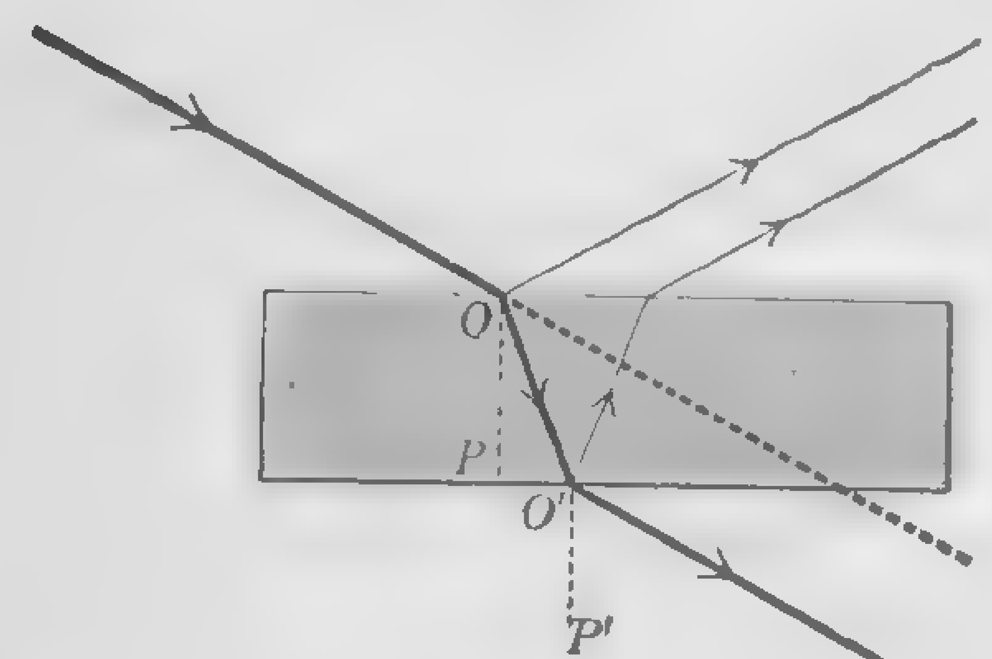


FIG. 393. Path of a ray through a medium bounded by parallel faces

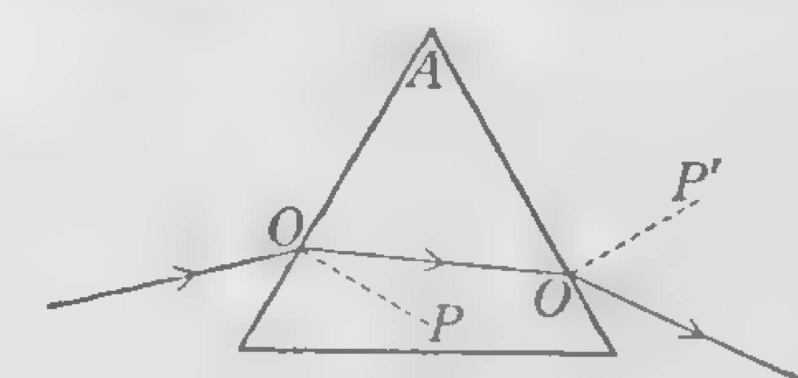


FIG. 394. Path of a ray through a prism

* All these experiments on reflection and refraction may be done effectively and conveniently by using disks of glass, like those used with the Hartl Optical Disk (Fig. 409), through which the beam can be traced.

As before, let a narrow beam of sunlight fall upon a glass prism cut out of a thick plate of glass. The greater portion of the light will pass through as shown in Fig. 394. The bendings, as already seen, are first toward and then away from the perpendiculars OP and $O'P'$ respectively. Since the sides of the prism are *not* parallel, the emergent beam is not parallel to the incident beam. If a prism of the same material having a larger angle A is used, it will be seen that there is a larger deviation of the light from its original direction. As in the case of the plate the beam will be split into reflected and transmitted portions on entering and on leaving the prism.

Similar experiments made with other substances have brought out the general law that *whenever light travels obliquely from one medium into another in which the speed is less, it is bent toward the perpendicular, and when it passes from one medium to another in which the speed is greater, it is bent away from the perpendicular, drawn into the second medium.*

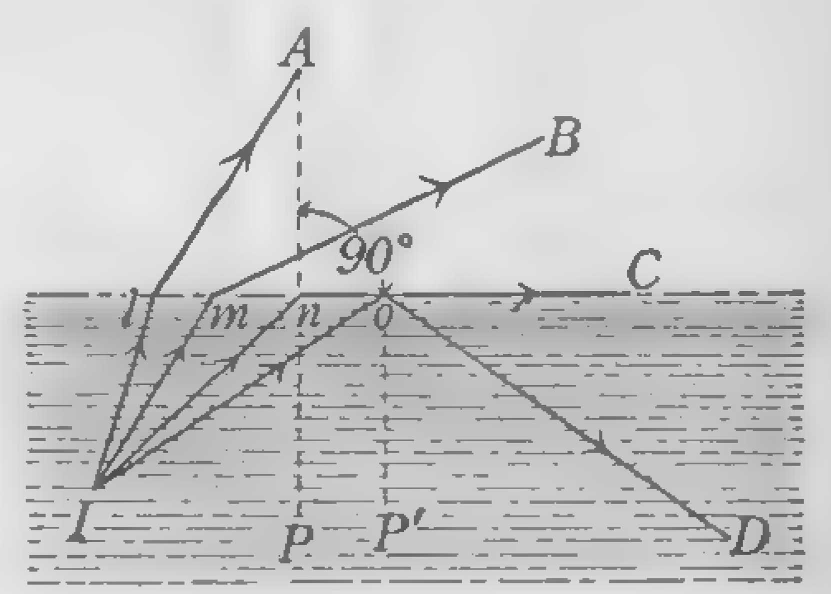


FIG. 395. Rays coming from a source I under water to the boundary between air and water at different angles of incidence

433. Total reflection; critical angle. Since rays emerging from a medium like water into one of less density, like air, are always bent *from* the perpendicular (see IlA, ImB, etc., Fig. 395), it is clear that if the angle of incidence on the under surface of the water is made larger and larger, a point must be reached at which the refracted ray is *parallel to the surface* (see InC, Fig. 395). It is interesting to inquire what will happen to a ray Io which strikes the surface at a still greater angle of incidence IoP'. It will not be unnatural to suppose that since the ray nC just grazed the surface, the ray Io will not be able to emerge at all. The following experiment will show that this is indeed the case.

Let a prism with three polished edges, a polished front, and a whitened back be held in the path of a narrow beam of sunlight,

as shown in Fig. 396. If the angle of incidence IOP is small, the beam will divide at O into a reflected and a transmitted portion, the former going to S', the latter to S (neglect the color for the present). Let the prism be rotated slowly in the direction of the arrow. A point will be reached at which the transmitted beam disappears completely, while at the same time the spot at S' shows an appreciable increase in brightness. Since the transmitted ray OS has totally disappeared, the whole of the light incident at O must be in the reflected beam. The angle of incidence IOP at which this occurs is called the *critical angle.* This angle for crown glass is 42.5°; for water, 48.5°; for diamond, 23.7°. The critical angle for any substance may be defined as the angle of incidence in that substance for which the angle of refraction into air is 90°.

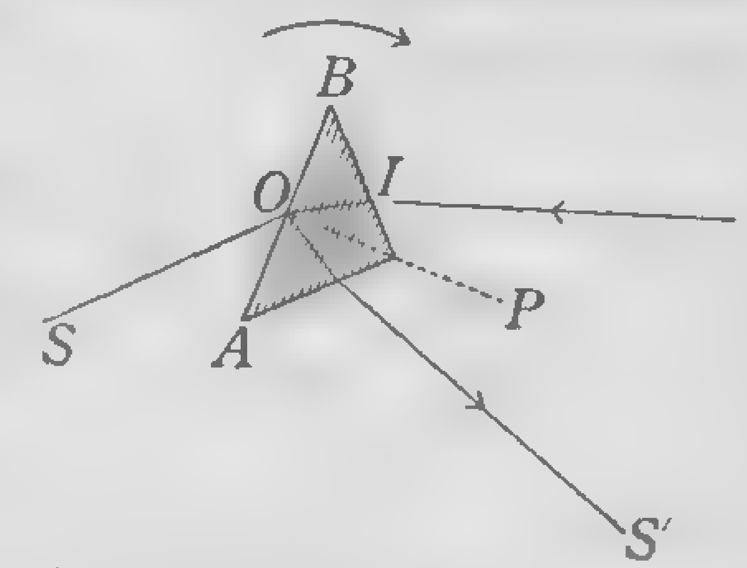


FIG. 396. Transmission and reflection of light at surface AB of a right-angle prism

We learn, then, that *when a ray of light traveling in any medium meets another in which the speed is greater, it is totally reflected if the angle of incidence is greater than a certain angle called the critical angle.*

434. Wave-theory explanation of refraction. Let one look vertically down upon a glass or tall jar full of water and place his finger on the side of the glass at the point at which the bottom appears to be, as seen through the water (Fig. 397). In every case it will be found that the point touched by the finger will be at a distance below the surface of the water about equal to three fourths of the entire depth of the water.

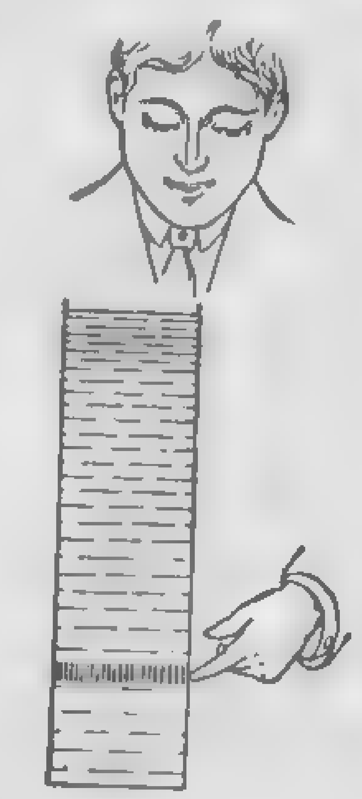


FIG. 397. Apparent depth of a body of water

According to the wave theory this effect is due to the fact that the speed of light is less in water than in air. Thus, consider a wave which originates at any point P (Fig. 398) beneath a surface of water and spreads from that point with equal speed in all directions. At the instant at which the front

of this wave first touches the surface at o it will, of course, be of spherical form, having P as its center. Let aob be a section of this sphere. An instant later, if the speed had not changed in passing into air, the wave would have still had P as its center, and its form would have coincided with the dotted line co_1d, so drawn that ac, oo_1, and bd are all equal. But if the velocity in air is *greater* than in water, then at the instant considered the disturbance will have reached some point o_2 instead of o_1, and hence the emerging wave will actually have the form of the heavy line co_2d instead of the dotted line co_1d. Now this wave co_2d is more curved than the old wave aob, and hence it has its center at some point P' above P. In other words, the wave has bulged upward in passing from water into air. Therefore, when a section of this wave enters the eye at E, the wave appears to originate not at P but at P', for the light actually comes to the eye from P' as a center rather than from P. We conclude, therefore, *that if light travels more slowly in water than in air, all objects beneath the surface of water ought to appear nearer to the eye than they actually are.* This is precisely what we found to be the case in our experiment with the tall jar of water (p. 401).

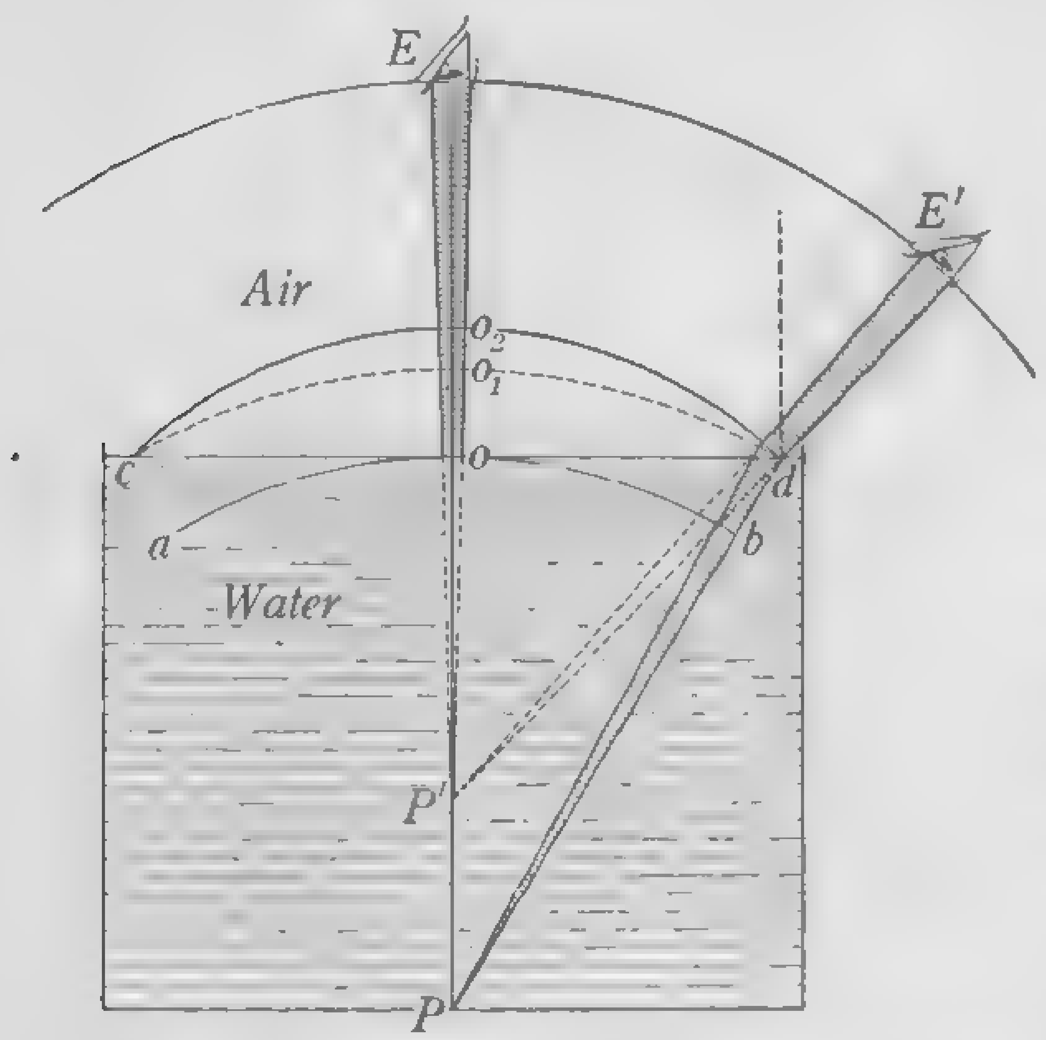


FIG. 398. Representing a wave emerging from water into air

Furthermore, since when the eye is in any position other than E, for example E', the light travels to it over the broken path PdE', the construction shows that light is always bent away from the perpendicular when it passes obliquely into a medium in which the speed is greater. If it had passed into a medium of less speed, the point P would have appeared

CHRISTIAN HUYGENS (1629–1695)

Great Dutch physicist, mathematician, and astronomer; discovered the rings of Saturn; made important improvements in the telescope; invented the pendulum clock (1656); developed with marvelous insight the wave theory of light; discovered in 1690 the "polarization" of light. (The fact of double refraction was discovered by Erasmus Bartholinus in 1669, but Huygens first noticed the polarization of the doubly refracted beams and offered an explanation of double refraction from the standpoint of the wave theory)

THE GREAT TELESCOPE OF THE YERKES OBSERVATORY (UNIVERSITY OF CHICAGO)

This is the largest *refracting* telescope in the world. The objective is an achromatic lens (see § 472) 40 inches in diameter, which is mounted in a tube 63 feet long. In order to follow the apparent motions of the heavenly bodies due to the rotation of the earth, the entire tube and counterpoises, weighing 21 tons, are driven by a giant clock. The speed of the clock is controlled by a governor, similar in principle to that of Fig. 179. By means of electric motors the telescope may be pointed in any direction. It is then clamped to the clock, which keeps it pointed toward the same region of the sky as long as may be desired. The entire floor may be raised or lowered to accommodate the observer

depressed below its natural position, because the wave, on emerging into the slower medium, instead of bulging upward, would be flattened, and therefore would have its

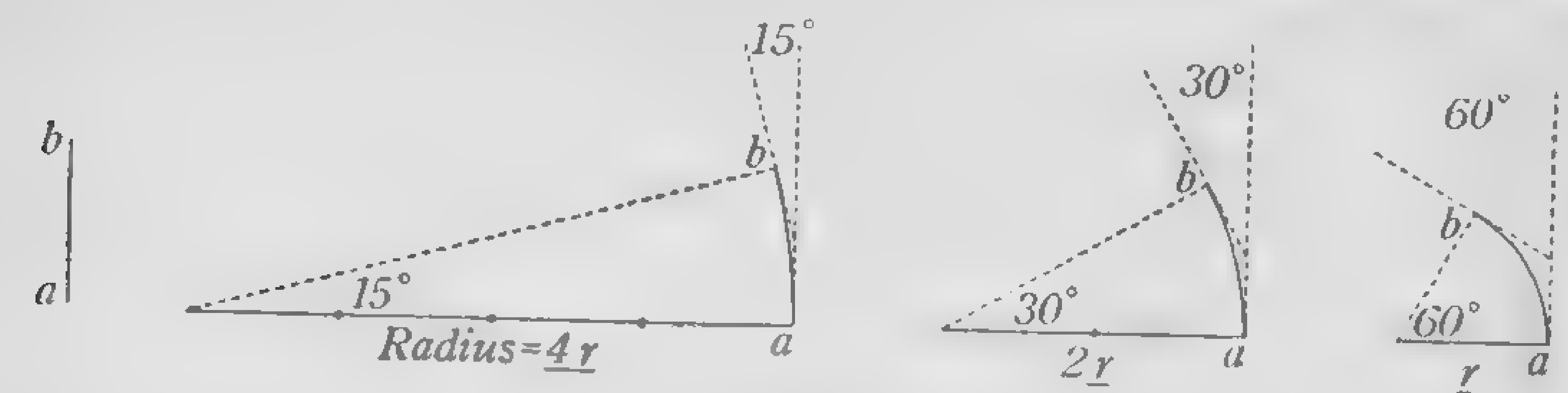


FIG. 399

center of curvature, or apparent point of origin, below P; hence the oblique rays would have appeared to be bent *toward* the perpendicular, as we found in § 432 to be the case.

435. The ratio of the speeds of light in air and water. The experiment with the tall jar of water in § 434 not only indicates qualitatively that the speed of light in air is greater than in water but it furnishes a simple means of determining the ratio of the two speeds. Thus, in Fig. 398 the line oo_2 represents just how far the wave travels in air while it is traveling the distance ac $(= oo_1)$ in water. Hence oo_2/oo_1 is the ratio of the speeds of light in air and in water.

Now the curvatures of the arcs co_2d and co_1d are measured by the reciprocals of their respective radii*; that is,

$$\frac{\text{Curvature of } co_2d}{\text{Curvature of } co_1d} = \left(\frac{\dfrac{1}{dP'}}{\dfrac{1}{dP}}\right) = \frac{dP}{dP'}. \qquad (1)$$

* The pupil can easily see that the amount of curvature of an arc varies inversely with the radius by considering a little straight piece of steel watch spring ab (Fig. 399) which may be bent to various degrees of curvature. As the bit of spring is bent successively into increasing curvatures of, say, 15°, 30°, and 60°, the radii of curvature diminish from $4r$ to $2r$ to r. In general, then, *the curvature of an arc is measured by the reciprocal of its radius.* It is on precisely the same principle that we say, "the pressure of the atmosphere is measured by the height of the barometer," since the one is proportional to the other.

Now when the arcs are *small*, a condition which in general is realized in experimental work on account of the smallness of the pupil of the eye (see E and E' of Fig. 398), their curvatures are for all practical purposes proportional to the extent to which they bulge out from the straight line *cod* *; that is,

$$\frac{\text{Curvature of } co_2d}{\text{Curvature of } co_1d} = \left(\frac{oo_2}{oo_1}\right) = \frac{\text{speed in air}}{\text{speed in water}}. \qquad (2)$$

From (1) and (2) we get

$$\frac{\text{Speed in air}}{\text{Speed in water}} = \frac{dP}{dP'}. \qquad (3)$$

But in looking vertically downward, as in the experiment with the jar of water, dP/dP' becomes oP/oP'; hence,

$$\frac{\text{Speed in air}}{\text{Speed in water}} = \frac{oP}{oP'} = \frac{\text{real depth}}{\text{apparent depth}}. \qquad (4)$$

But in our experiment we found the ratio of the real depth to the apparent depth to be 4/3; that is, that $oP/oP' = 4/3$. We conclude, therefore, that light travels three fourths as fast in water as in air.

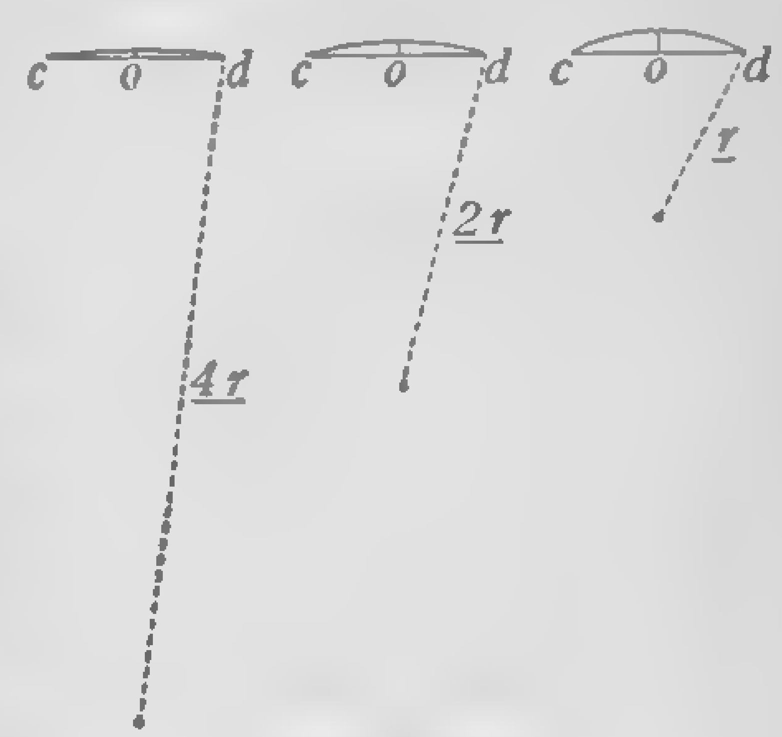


FIG. 400

The fact that the value of this ratio, as determined by this indirect method, is exactly the same as that found by Foucault and Michelson (see opposite page 390) by direct measurement (§ 418) constitutes one of the great successes of the wave theory.

436. Index of refraction. *The ratio of the speed of light in air to its speed in any other medium is called the index of refraction of that medium.* It is evident that the method employed

* The pupil can readily perceive the truth of this statement by inspection of Fig. 400, where we have very small arcs of different curvatures drawn upon chords of equal length. The curvatures are as 1 to 2 to 4 (on account of the radii) and the bulges (since the arcs are small) are also, for all practical purposes, as 1 to 2 to 4.

in the last paragraph for determining the index of refraction of water can be easily applied to any transparent medium whether liquid or solid.* The refractive indices of some of the commoner substances are as shown in the following table.

Water	1.33	Crown glass	1.53
Alcohol	1.36	Flint glass	1.67
Turpentine	1.47	Diamond	2.47

* To show the extreme beauty, simplicity, and accuracy of this method of getting index of refraction it is suggested that the teacher use the following method in his laboratory work.

A very sharp pencil must be used for this exercise. Make a dot P on a sheet of paper. Put the glass plate (Fig. 401 (1)) on the sheet so that the edge of the

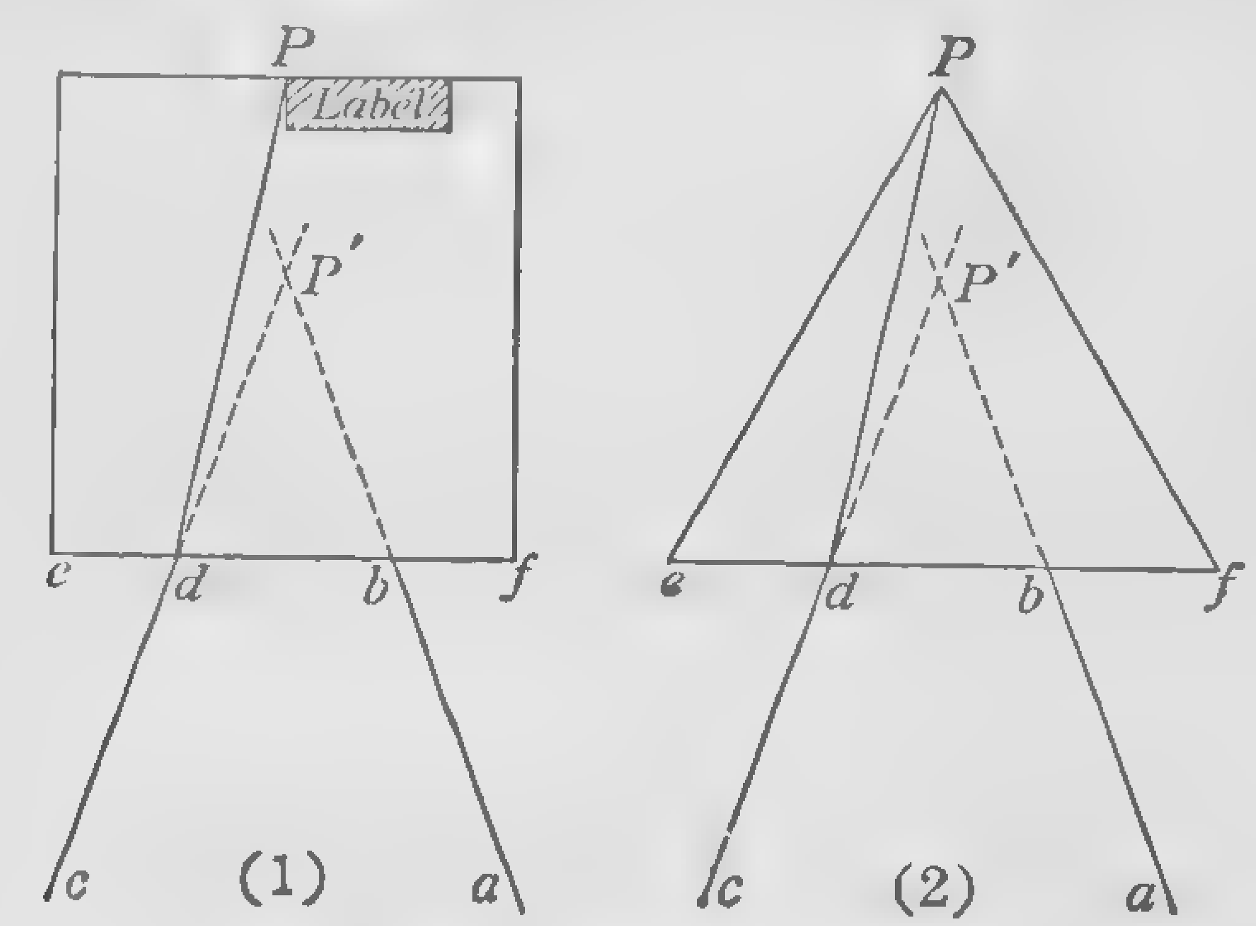


FIG. 401. Index of refraction

label pasted around the edge of the glass coincides with the dot (or in case a prism (Fig. 401 (2)) is used, let the apex P coincide with the dot). Draw the base line *ef* and the other sides of the glass, holding it firmly down meanwhile. Be sure that at no time during the exercise does the glass slip the slightest from its first position. Lay a ruler upon the paper in a slantwise position *cd* (not touching the glass), and with one eye closed, make its edge point exactly at the apparent position of P as seen through the glass. If you are now sure that your ruler did not push the glass out of position, draw a line *cd* with the sharp pencil. Similarly, draw another line *ab* about as far to the right of the center as *cd* is to the left. Remove your glass and complete the drawing as indicated in the diagram.

P' is the apparent position of P. As you have already learned from your text, the ratio of the velocities of light in air and glass is found by dividing dP by dP'. Measure these distances very carefully to 0.1 mm., and calculate the index of refraction to two decimal places. Make two or three more trials and compare results.

Summary. In passing into an optically denser medium light is bent toward the perpendicular drawn to the new medium, and in passing into an optically rarer medium it is bent away from the perpendicular.

Total reflection occurs when light tends to pass from a denser to a rarer medium at an angle greater than the critical angle.

The index of refraction of a substance is the ratio of the velocity of light in the air to its velocity in that substance.

QUESTIONS AND PROBLEMS*

1. Draw diagrams to show in what way a beam of light is bent (1) in passing through a prism; (2) in passing obliquely through a plate-glass window.

2. Explain how the prism glass of the automobile headlight (Fig. 402) deflects the beam of light upon the road.

FIG. 402. Cross section of a headlight lens

3. Fig. 403 represents a section of a plate of prism glass. Explain why glass of this sort is so much more efficient than ordinary window glass in illuminating the rears of dark stores on the ground floor in narrow streets.

4. If a penny is placed in the bottom of a vessel in such a position that the edge just hides it from view (Fig. 404), it will become visible as soon as water is poured into the vessel. Explain.

5. A stick held in water appears bent, as shown in Fig. 405. Explain.

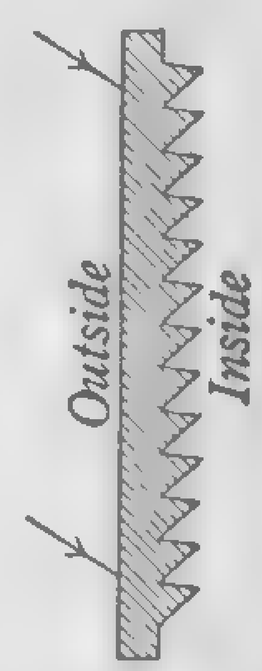


FIG. 403. A Luxfer prism glass

6. A glass prism placed in the position shown in Fig. 406 is the most perfect reflector known. Why is it better than an ordinary mirror?

7. Diagonal eyepieces which contain a right-angle prism of crown glass (Fig. 407) are used on astronomical telescopes in viewing celestial objects at a high altitude. Explain.

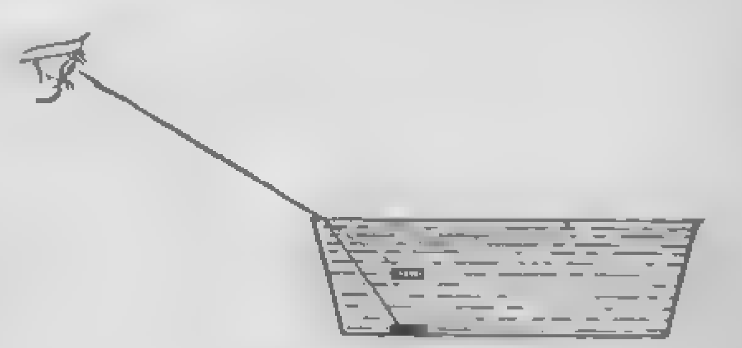


FIG. 404

8. If light travels with a velocity of 186,000 mi. per sec. in air, what is its velocity in water, in crown glass, and in diamond? (See table of indices of refraction, p. 405.)

9. A pebble lying at the bottom of a spring 12 in. deep appears to be but 9 in. below the surface. Explain, by aid of a diagram, the cause of the apparent shallowness of the water.

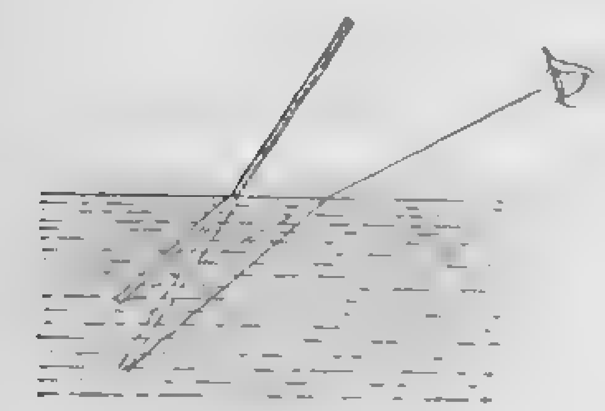


FIG. 405

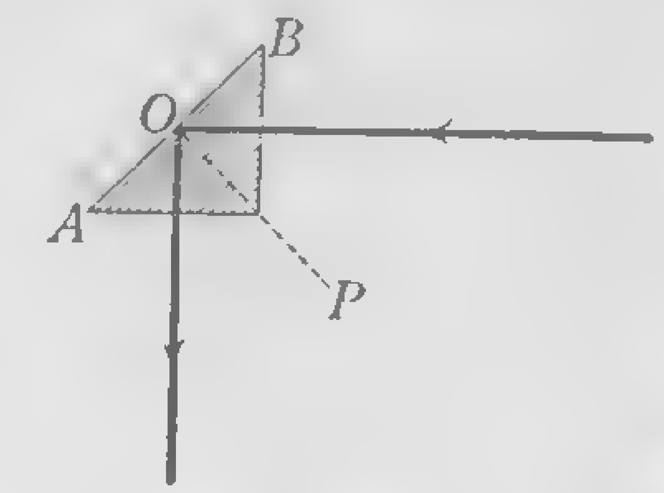


FIG. 406

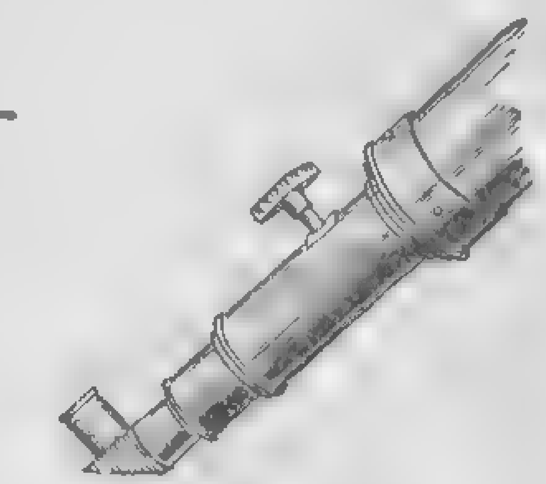


FIG. 407. A diagonal eyepiece

10. Show by a diagram and explanation what is meant by critical angle.

11. Will a beam of light going from water into flint glass be bent toward or away from the perpendicular drawn into the glass?

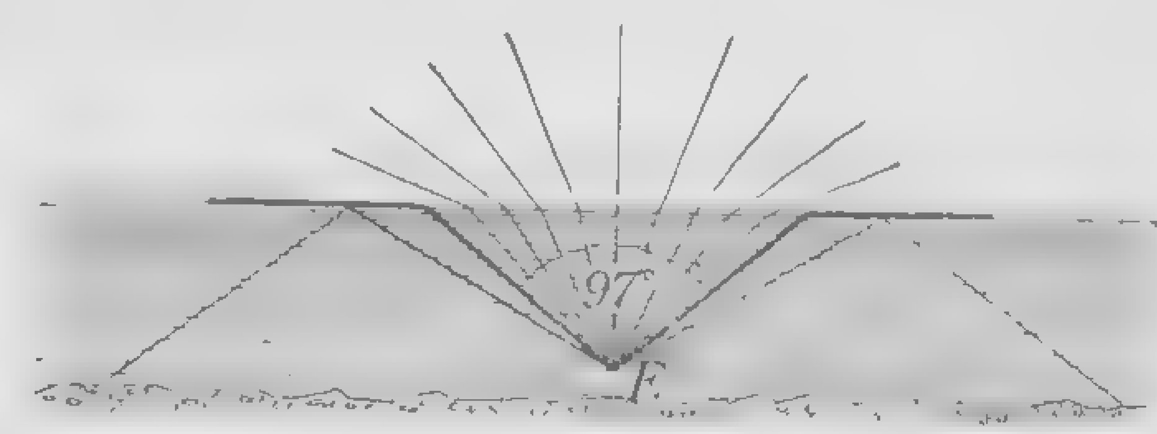


FIG. 408. To an eye under water all external objects appear to lie within a cone whose angle is 97°

12. At what angle with the horizontal must a fish beneath the surface of water look in order to see the setting sun? (See Fig. 408.)

* Supplementary questions and problems for Chapter XVIII are given in the Appendix.

CHAPTER XIX

IMAGE FORMATION

Images formed by Lenses

437. Focal length of a convex lens. Let a beam of light fall upon the convex glass of a Hartl optical disk (Fig. 409), or, in case this is not available, let a convex lens be held in the path of a beam of sunlight which enters a darkened room, where it is made visible by means of chalk dust or of smoke. The beam will be found to converge to a focus F, as shown in Fig. 410. Place a screen at F. The spot of intense brightness represents a very small image of the sun. Measure the distance from this lens to the "burning spot."

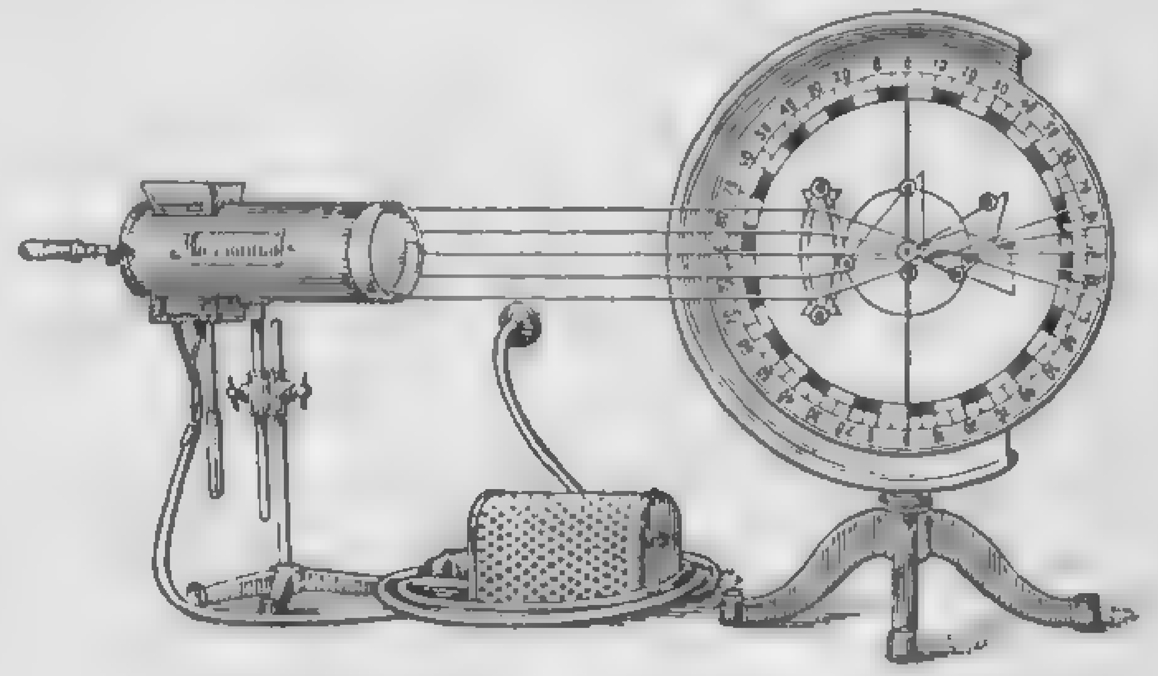


Fig. 409. Hartl optical disk

The explanation is as follows: The waves from the sun or any distant object are without any appreciable curvature when they strike the lens; that is, they are so-called *plane waves* (see Fig. 410). Since the speed of light is less in glass than in air, the central portions of these waves are retarded more than the outer portions in passing through the lens. Hence, on emerging from the lens the waves are concave instead of plane, and close in to a center, or *focus*, at F.

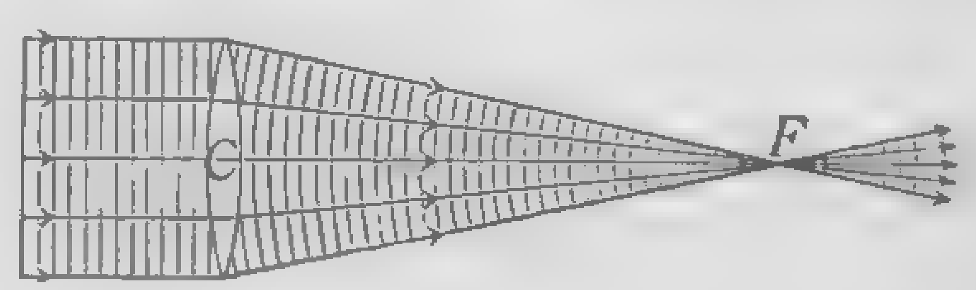


Fig. 410. Principal focus F and focal length CF of a convex lens

A second way of looking at the phenomenon is to think of the "rays" which strike the lens as being bent by it, in accordance with the laws given in § 432, so that they all pass through the point F.

The line through the point C (the *optical center*) of the lens, perpendicular to its faces, is called the *principal axis.*

The point F at which rays parallel to the principal axis (incident plane waves) are brought to a focus is called the *principal focus.*

The distance CF from the center of the lens to the principal focus is called the *focal length* (f) of the lens.

Turn the lens used in the previous experiment toward a distant house and place a card (or, better, a mounted tracing-cloth screen) at the principal focus F (see Fig. 411) as found by the "burning spot." A sharp image of the distant house will be formed upon the screen. If the eye is placed at least a foot directly behind the screen and the latter removed, the image of the house will be seen at the exact place where the screen was located. This sort of image which can be caught on a screen is called a *real image.*

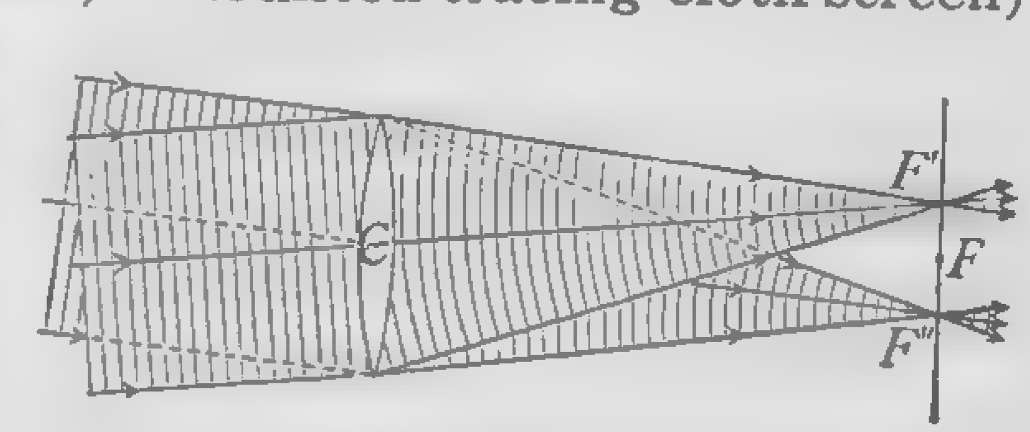


Fig. 411. Focal plane of a convex lens

The plane $F'FF''$ (Fig. 411) in which plane waves (parallel rays) coming to the lens from slightly different directions, as from the top and bottom of the distant house, all have their foci F', F'', etc. is called the *focal plane* of the lens. This is the position of a camera film with reference to its lens when a distant object is being photographed.

Since the curvature of any arc is defined as the reciprocal of its radius (see footnote, p. 403), *the curvature which a lens impresses on an incident plane wave is equal to $1/f$.* Moreover, no matter what the curvature of an incident wave may be, *the lens will always change the curvature by the same amount, $1/f$.*

438. Conjugate foci. If a point source of light is placed at F (Fig. 410), it is obvious that the light which goes through the lens must exactly retrace its former path; that is, its waves will be rendered plane or its rays parallel by the lens. But if the point source P is at a distance D_o greater than f (Fig. 412), then the waves from P upon striking the lens have a curvature $1/D_o$ which is less than their former

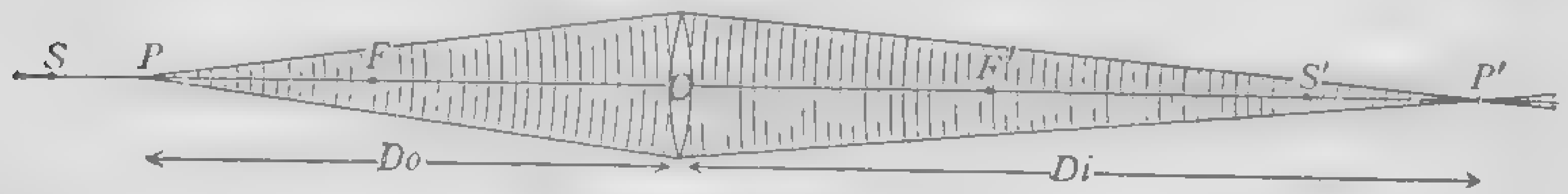


FIG. 412. Conjugate foci

curvature, $1/f$. Since the lens was able to subtract all the curvature from waves coming from F (Fig. 410) and render them plane, by subtracting the same curvature from the flatter waves from P (Fig. 412) it must render them concave; that is, the rays after passing through the lens are converging and intersect at P'. If the source is placed at P', obviously the rays will meet at P. Points such as P and P', so related that one is the image of the other, are called *conjugate foci.*

439. Formula for conjugate foci; secondary foci. Since in Fig. 412 the curvature of the wave when it emerges from the lens is opposite in direction to its curvature when it reaches the lens, the *sum* of these curvatures, $1/D_o + 1/D_i$, represents the power of the lens to change the curvature of the incident wave, which by § 437 is $1/f$. Hence

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}; \qquad (1)$$

that is, *the sum of the reciprocals of the distances of the conjugate foci from the lens is equal to the reciprocal of the focal length.* If $D_o = D_i$, then the equation shows that both D_o and D_i are equal to $2f$. That is, if a point source of light is placed at S two focal lengths from the lens (Fig. 412), the light passing from S through the lens will be brought to a focus at S', also two focal lengths from the lens.

The two conjugate foci S and S' which are at equal distances from the lens are called the *secondary foci.*

440. Images of objects. Let a candle or electric-light bulb be placed between the principal focus F and the secondary focus S

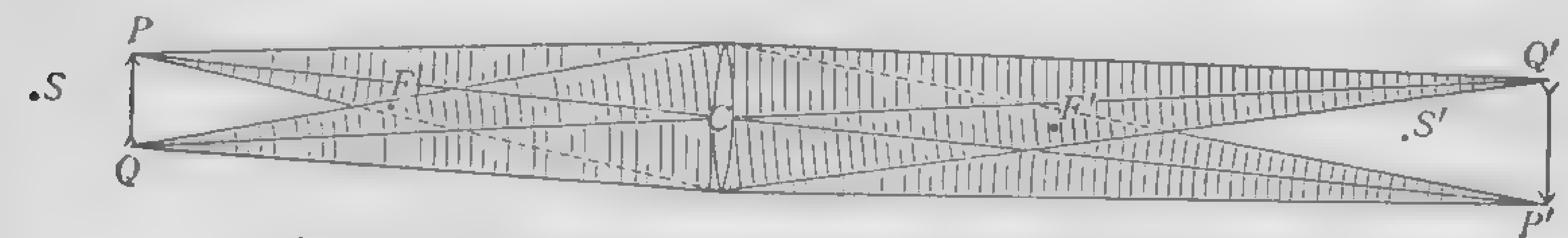


FIG. 413. Formation of a real image by a lens

at PQ (Fig. 413), and let a screen of draughtman's tracing cloth be placed at $P'Q'$. An enlarged inverted image will be seen upon the screen when viewed from either side.

This image is formed as follows: All the light which strikes the lens from the point P is brought together at a point P'. *The location of this image P' must be on a straight line drawn from P through C; for any ray passing through C will remain parallel to its original direction, since the portions of the lens through which it enters and leaves may be regarded as small parallel planes* (see § 432). *The image $P'Q'$ is therefore always formed between the lines drawn from P and Q through C.*

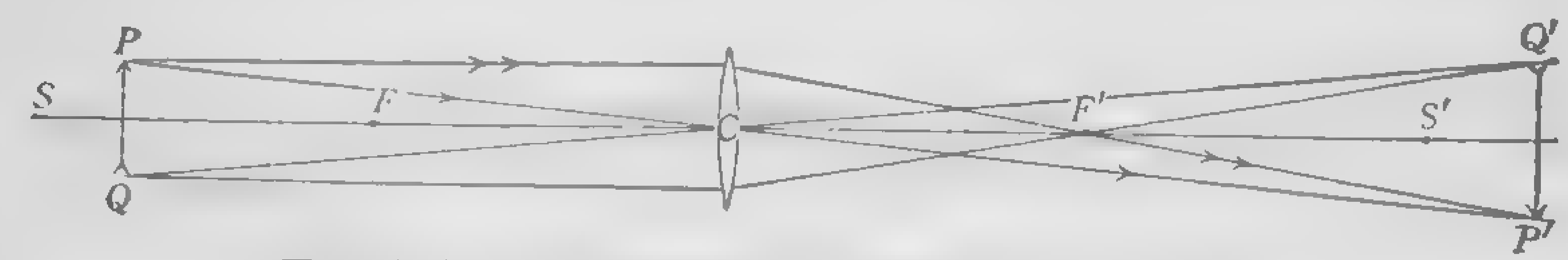


FIG. 414. Ray method of constructing an image

If the focal length f and the distance of the object D_o are known, the distance of the image D_i may be obtained easily from formula (1).

The position of the image may also be found graphically as follows: Of the cone of rays passing from P to the lens, that ray which is parallel to the principal axis must, by § 437, pass through the principal focus F. The intersection of this line with the straight line through C locates the image P' (see Fig. 414). Q', the image of Q, is located similarly.

441. Size of image. Since the image and object are always between the intersecting straight lines PP' and QQ', the similar triangles PCQ and $P'CQ'$ show that

$$\frac{PQ}{P'Q'} = \frac{D_o}{D_i}; \qquad (2)$$

that is,

$$\frac{\text{Length of object}}{\text{Length of image}} = \frac{\text{distance of object from lens}}{\text{distance of image from lens}}.$$

From Fig. 414 and formulas (1) and (2) we see that

1. When the object is at S, the image is at S', and image and object are of the same size.
2. As the object moves out from S to a great distance, the image moves from S' up to F', becoming smaller and smaller.

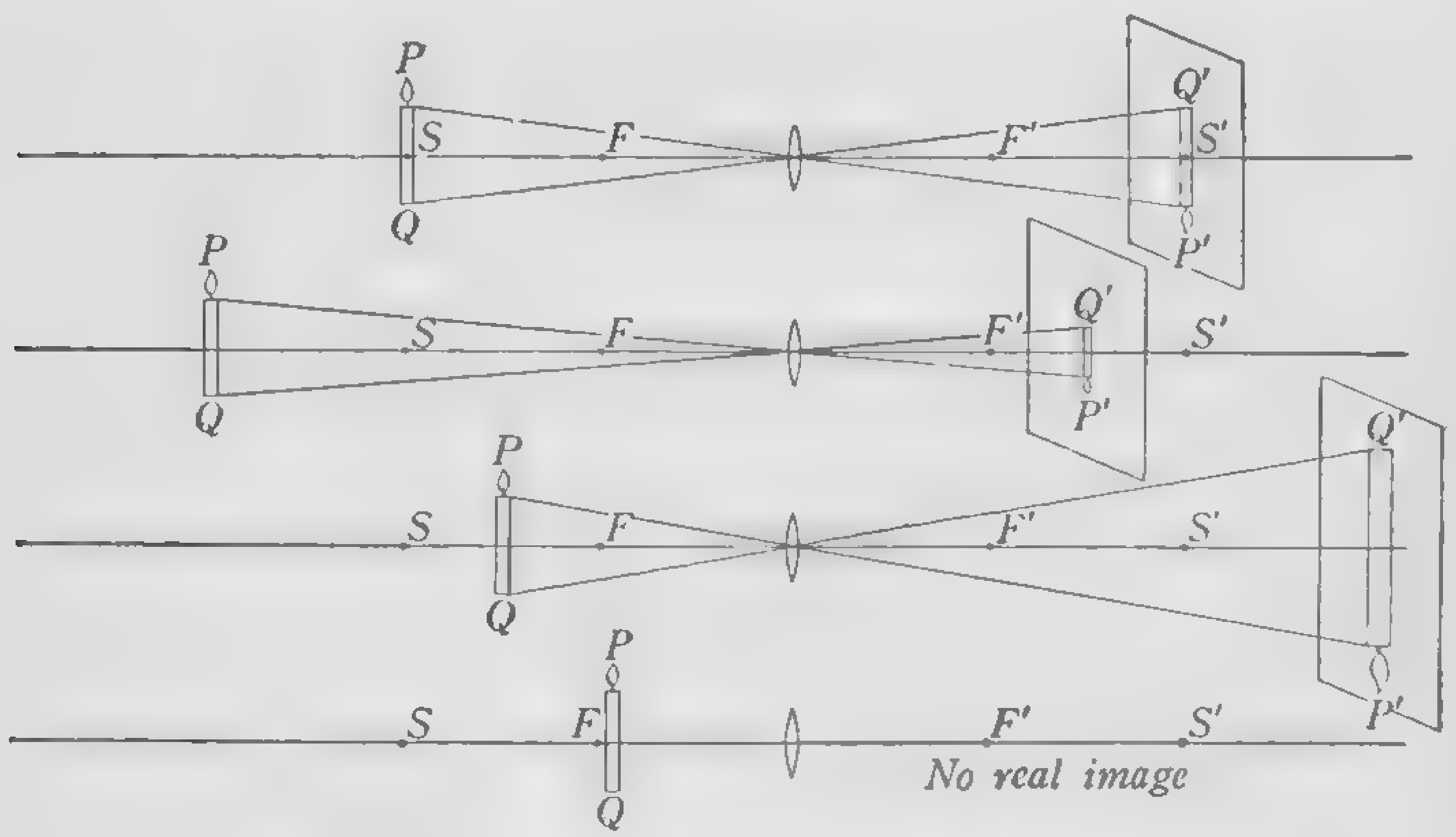


FIG. 415. Relative sizes of image and object

3. As the object moves from S up to F, the image moves out to a very great distance to the right, becoming larger and larger.
4. When the object is at F, the emerging waves are plane (the emerging rays are parallel), and no real image is formed.

These four conclusions are represented by the diagrams of Fig. 415. Let these conclusions be experimentally tested by use of the object, lens, and screen used in § 440.

442. Virtual image. We have seen that when the object is at F the waves after passing through the lens are plane. If, then, the object is nearer to the lens than F, the emerging waves, although reduced in curvature, will still be convex, and, if received by an eye at E, will appear to come from a point P' (Fig. 416). Since, however, no light actually goes from P to P' on its way to the eye, this sort of image is called a *virtual image*. Such an image cannot be projected upon a screen as a real image can, but must be observed by an eye.

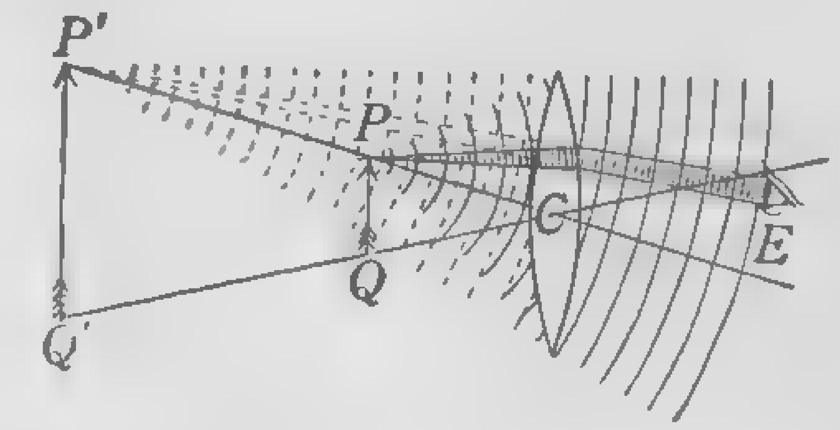


FIG. 416. Virtual image formed by a convex lens

The graphical location of a virtual image may be accomplished precisely as in the case of a real image (§ 440). It will be seen that in this case (Figs. 416 and 417) *the image is enlarged and erect.*

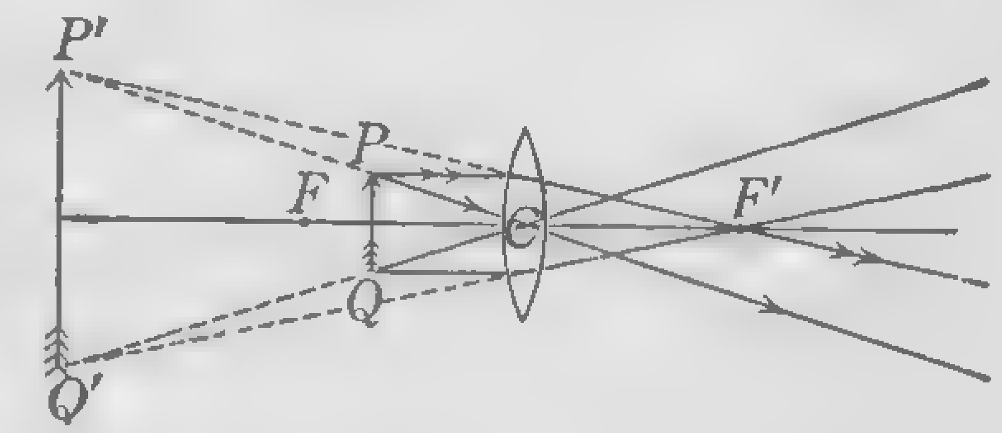


FIG. 417. Ray method of locating a virtual image in a convex lens

443. Image in concave lens. When a plane wave strikes a concave lens, it must emerge as a divergent wave, since the middle of the wave is retarded by the glass less than the edges (Fig. 418). The point F from which plane waves appear to come after passing through such a lens is the principal focus of the lens. For the same reason as in the case of the convex lens the centers of the transmitted waves from P and Q (Fig. 419) — that is, the images P' and Q' — must lie upon the lines PC and QC; and since the curvature is increased by the lens, they must lie closer to the lens than P and Q. Fig. 419 illustrates the way in which such a lens forms an image. This image is

FIG. 418. Virtual focus of a concave lens

always *virtual, erect,* and *diminished.* The graphical method of locating the image is shown in Fig. 420.*

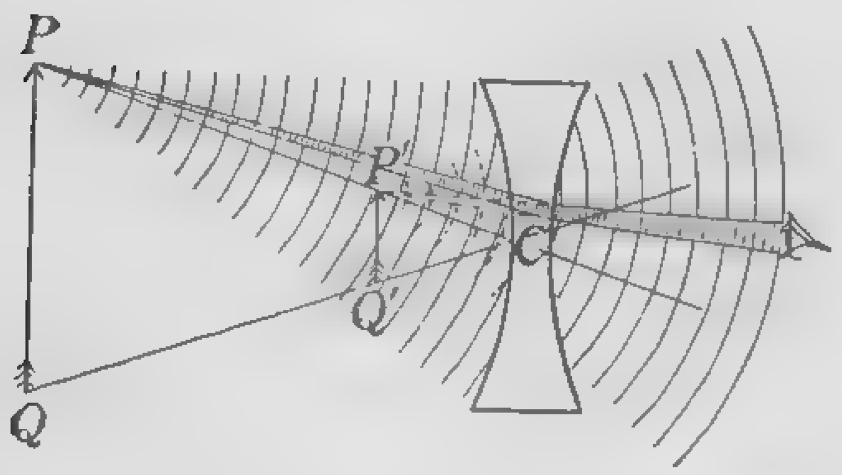


FIG. 419. Image in a concave lens

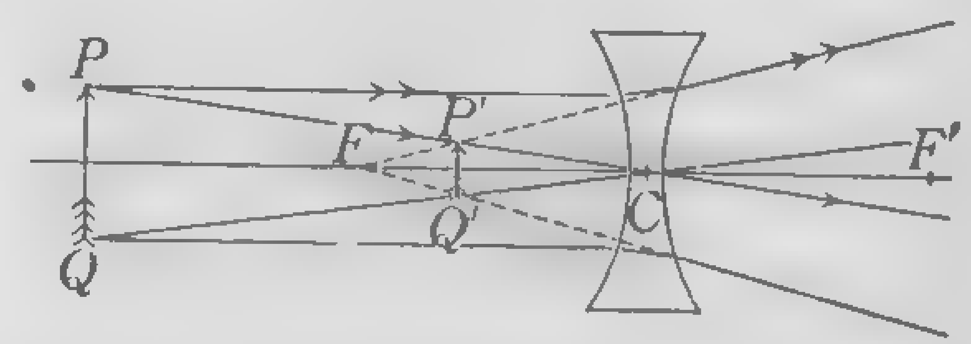


FIG. 420. Ray method of locating an image in a concave lens

SUMMARY. 1. **Real images are inverted; virtual images are erect.** The length of all images is given by

$$\frac{L_o}{L_i}=\frac{D_o}{D_i},$$

where L_o and L_i denote the length of object and image respectively, and D_o and D_i their distances from the lens or mirror.

2. Convex lenses have a converging effect upon rays (always diminish the curvature of the waves.)

a. If the object is *more distant* than the principal focus, *the image is real* and (1) *enlarged* when the object is between the principal focus and twice the focal length; (2) *diminished* when the object is beyond two focal lengths.

b. If the object is *less distant* than the principal focus, *the image is virtual* and *always enlarged.*

3. Concave lenses have a diverging effect upon the rays (always increase the curvature of the waves). The image is *always virtual* and *diminished* for any position of the object.

4.
$$\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{f}. \qquad (§ 439)$$

This formula may be applied in all cases, provided that the following points are borne in mind:

a. D_o is always to be taken as positive.

* Laboratory experiments on the formation of images by lenses should follow this discussion. See, for example, Experiment 58 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

b. D_i is to be taken as positive for real images and negative for virtual images.

c. f is to be taken as positive for converging systems (convex lenses) and negative for diverging systems (concave lenses).

QUESTIONS AND PROBLEMS

1. What is the difference between a real and a virtual image?

2. Show, by means of a diagram, the relative positions of object, image and lens in order that a virtual image may be produced by a convex lens.

3. When does a convex lens form a real, and when a virtual image? When an enlarged, and when a diminished image? When an erect, and when an inverted one?

4. Describe the image formed by a concave lens. Why can it never be larger than the object?

5. Rays diverge from a point 20 cm. in front of a converging lens whose focal length is 4 cm. At what point do the rays come to a focus?

6. What is the focal length of a lens if the image of an object 10 ft. away is 3 ft. from the lens?

7. If the object in Problem 6 is 6 in. long, how long will the image be?

8. An object 2 cm. long was placed 10 cm. from a converging lens, and the image was formed 40 cm. from the lens on the other side. Find the focal length of the lens and the length of the image.

9. At what distance from a convex lens having a focal length of 12 cm. must an object be placed in order to form a real image twice as long as the object?

10. Given a convex lens of 18 in. focal length, where should an object be placed to enable the lens to form a real image three times the length of the object?

11. The works of a watch are held 1.5 in. from a jeweler's eye lens which has a focal length of 1.75 in. How many inches from the lens is the virtual image formed? How many times as great in diameter are the image wheels as the actual wheels?

Images in Mirrors

444. Image of a point in a plane or a curved mirror. We are all familiar with the fact that to an eye at E (Fig. 421), looking into a plane mirror mn, a pencil point at P appears to be at some point P' behind the mirror. We are able in the laboratory to find experimentally the exact location of this image P' with respect to P and the mirror, but we may also obtain this location from theory as follows: Consider a light wave which originates in the point P (Fig. 421) and spreads in all directions. Let aob be a section of the wave at the instant at which it reaches the reflecting surface mn.

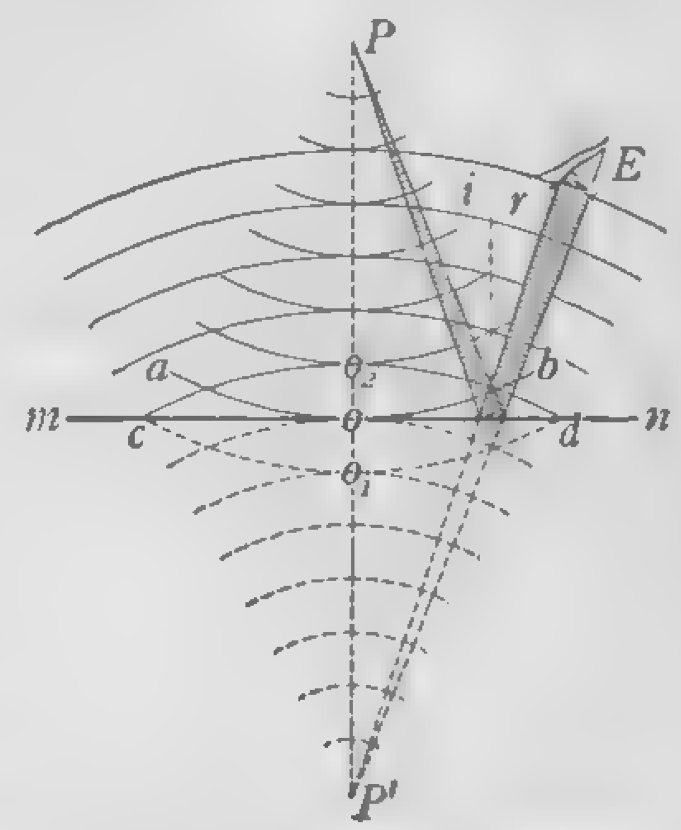


FIG. 421. Wave reflected from a plane surface

An instant later, if there was no reflecting surface, the wave would have reached the position of the dotted line co_1d. Since, however, reflection took place at mn, and since the reflected wave is propagated backward with exactly the same velocity with which the original wave would have been propagated forward, at the proper instant the reflected wave must have reached the position of the line co_2d, so drawn that oo_1 is equal to oo_2. Now the wave co_2d has its center at some point P', and it will be seen that P' must lie just as far below mn as P lies above it, for co_1d and co_2d are arcs of equal circles having the common chord cd. For the same reason, also, P' must lie on the perpendicular drawn from P through mn.

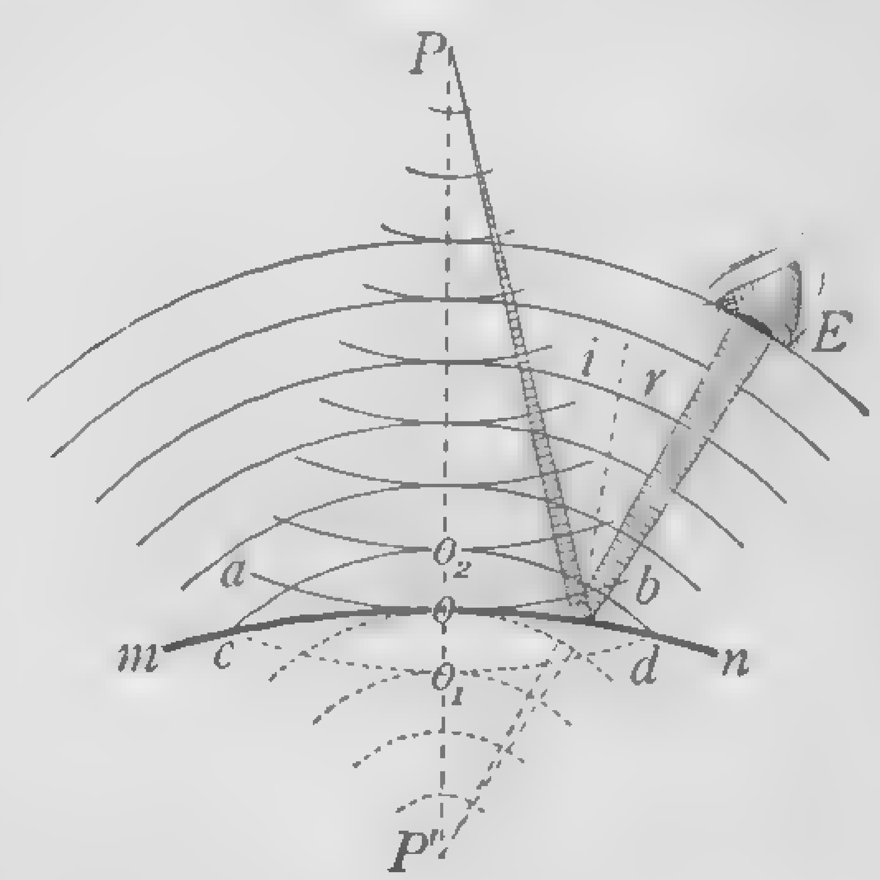


FIG. 422. Wave reflected from a convex surface

When, then, a section of this reflected wave co_2d enters the eye at E, the wave appears to have originated at P' and not at P, for the light actually comes to the eye from P' as a center rather than from P. Hence P' is the image of P. We learn, therefore, that *the image of a point in a plane mirror lies on the perpendicular drawn from the point to the mirror and is as far back of the mirror as the point is in front of it.*

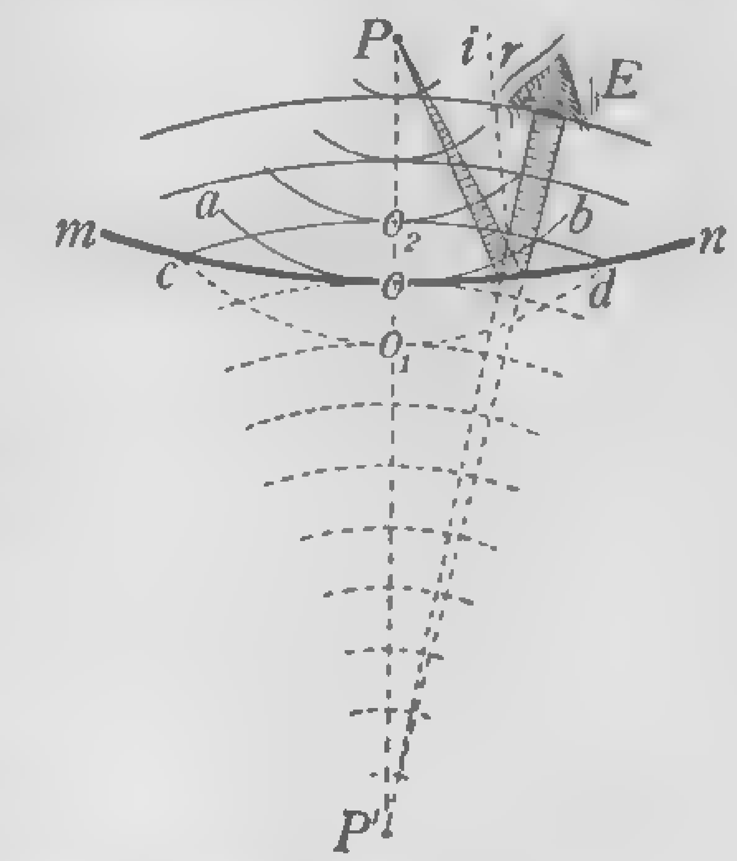


FIG. 423. Wave reflected from a concave surface

Precisely the same construction applied to curved mirrors shows at once (Figs. 422 and 423) that *the image of a point in any mirror, plane or curved, must lie on the perpendicular drawn from the point to the mirror; but if the mirror is convex, the image is nearer to it than is the point, whereas if it is concave, the image, if formed behind the mirror at all (that is, if it is virtual), is farther from the mirror than is the point.*

445. Construction of image of object in a plane mirror. The image of an object in a plane mirror (Fig. 424) may be located by applying the law proved above for each of its points, that is, *by drawing from each point a perpendicular to the reflecting surface and extending it an equal distance on the other side.*

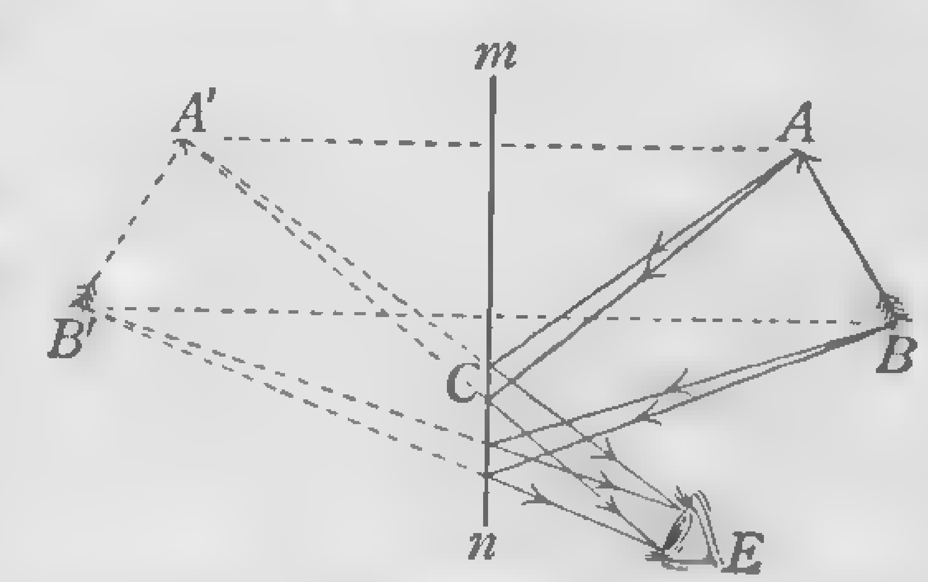


FIG. 424. Construction of image of object in a plane mirror

To find the path of the rays which come from any point of the object, such as A, to an eye placed at E, we have only to draw lines from the image A' of this point to the eye and connect the points of intersection of these lines with the mirror to the original point A. ACE is then the path of the rays.

Let a candle (Fig. 425) be placed exactly as far in front of a pane of window glass as a bottle full of water is behind it, both objects being on the same perpendicular drawn through the glass. The candle will appear to be burning inside the water. This explains a large class of familiar optical illusions, such as the "figure suspended in mid-air," the "bust of a person without a trunk," the "stage ghost," etc. In the last case the illusion is produced by causing the audience to look at the actors obliquely through a sheet of very clear plate glass, the edges of which are concealed by draperies. Images of strongly illuminated figures at one side then appear to the audience to be in the midst of the actors.

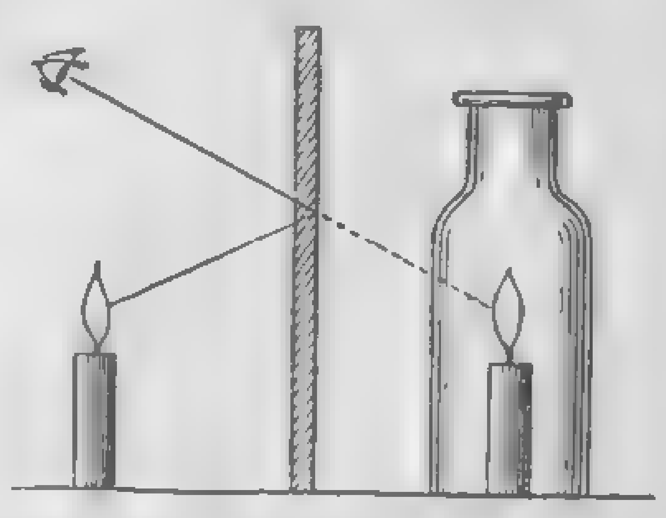


FIG. 425. Position of image in a plane mirror

446. Focal length of a curved mirror half its radius of curvature. The effect of a convex mirror on plane waves incident upon it is shown in Fig. 426. The wave which would at a given instant have been at co_1d is at co_2d, where $oo_1 = oo_2$. The center F from which the waves appear to come to the eye E is the *focus* of the mirror.

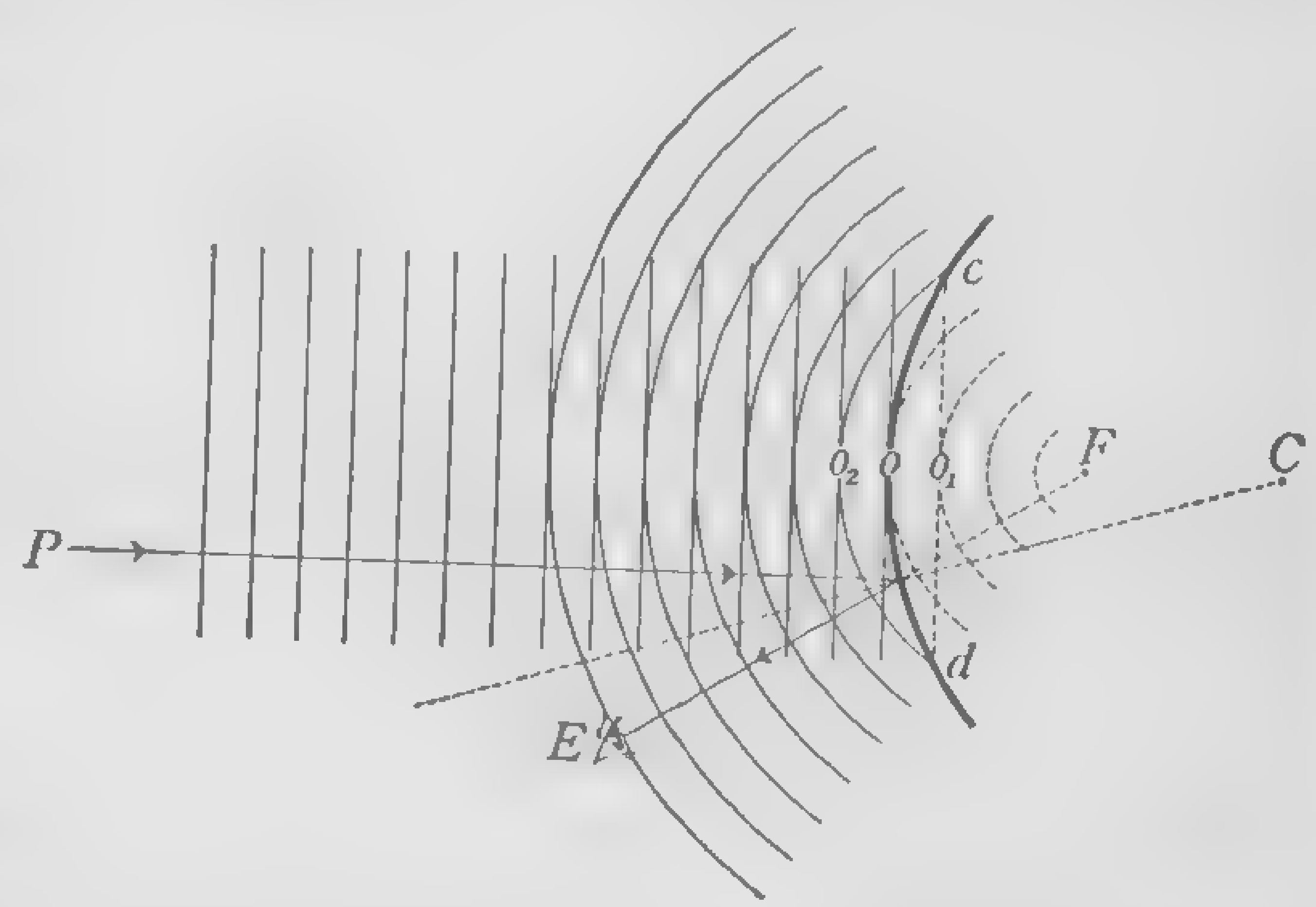
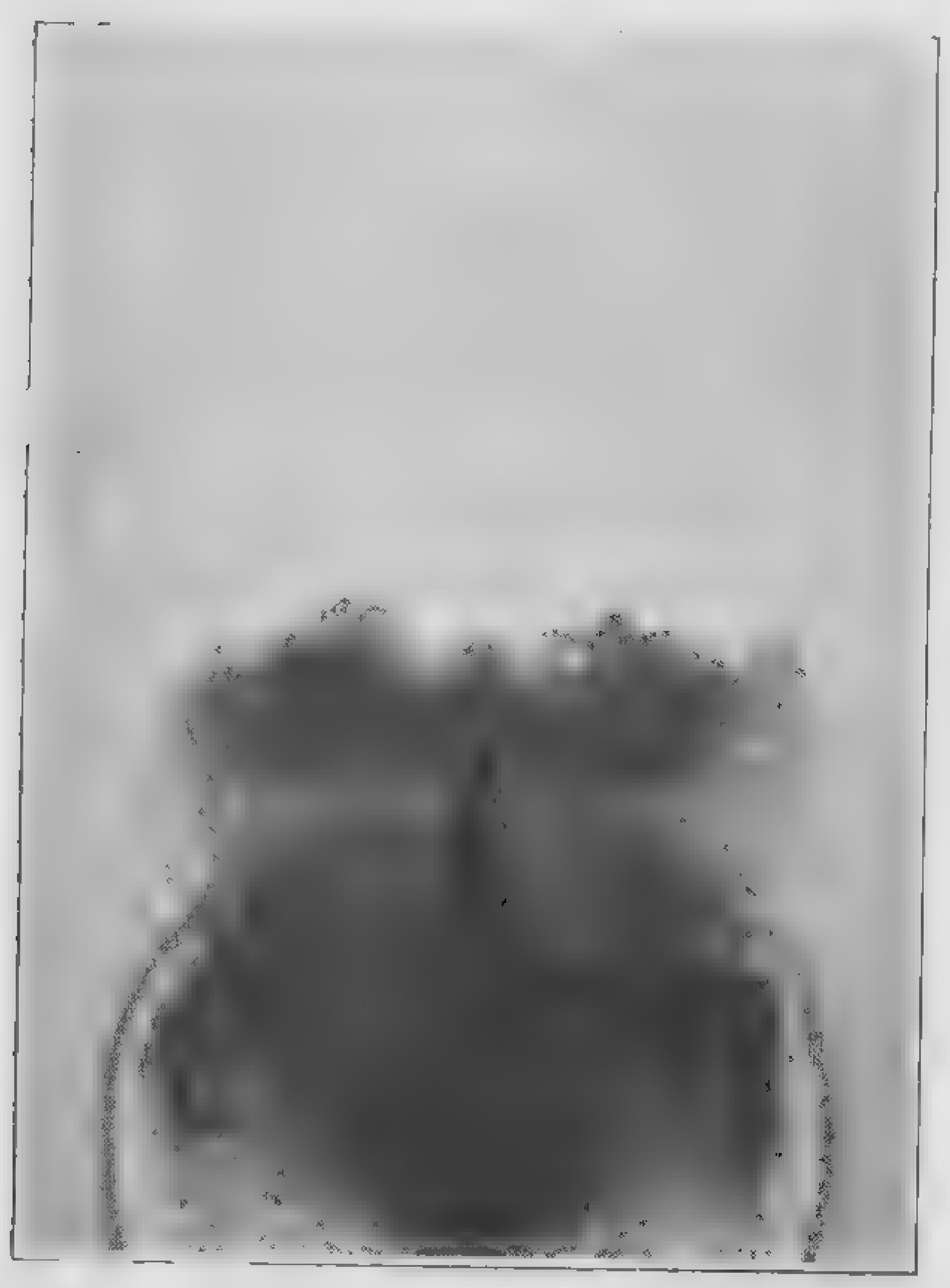


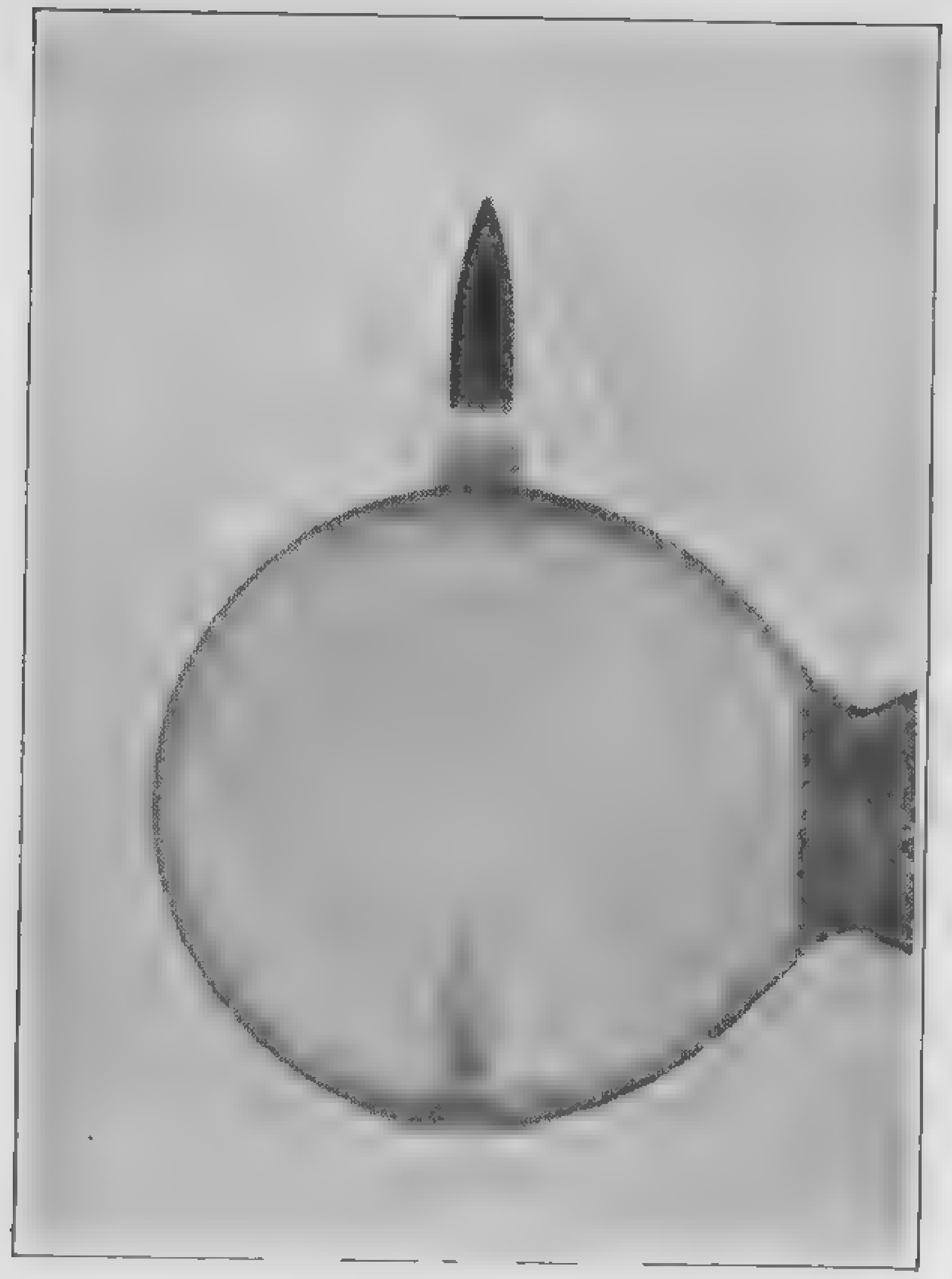
FIG. 426. Reflection of a plane wave from a convex mirror

Now so long as the arc *cod* is small its curvature may, without appreciable error, be measured by o_1o (see footnote, p. 404); that is, by the departure of the curved line *cod* from the straight line co_1d. Since o_1o was made equal to oo_2, we have $o_1o_2 = 2o_1o$; that is, the curvature $1/f$ of the reflected wave is equal to

SECTION OF A MOVING-PICTURE FILM SHOWING NEWTON C. BAKER TURNING HIS HEAD TO SPEAK TO GENERAL PERSHING

The moving-picture camera makes a series of snapshots upon a film, usually at the rate of 16 per second. The film is drawn past the lens with a jerky movement, being held at rest during the instant of exposure and moved forward while the shutter is closed. The pictures are $\frac{3}{4}$-inch high and 1 inch wide. Since 1 foot of film per second is drawn past the lens, a reel of film 1000 feet long (the usual length) contains 16,000 pictures. From the reel of negatives a reel of positives is printed for use in the projection apparatus. The optical illusion of "moving" pictures is made possible by a peculiarity of the eye called *persistence of vision.* To illustrate this let a firebrand be rapidly whirled in a circle. The spot of light appears drawn into a luminous arc. This phenomenon is due to the fact that we continue to see an object for a small fraction of a second after the image of it disappears from the retina. The period of time varies somewhat with different individuals. The so-called *moving* pictures do not move at all. In normal projection 16 brilliant stationary pictures per second appear in succession upon the screen, and during the interval between the pictures the screen is perfectly dark. It is during this period of darkness that the film is jerked forward to get the next picture into position for projection. The eye, however, detects no period of darkness, for on account of persistence of vision it continues to see the stationary picture not only during this period of darkness but dimly for an instant even after the next picture appears upon the screen. This causes the successive stationary pictures, which differ but slightly, to blend smoothly into each other and thus give the effect of actual motion





SHADOW PHOTOGRAPH OF A BULLET IN FULL FLIGHT

These are shadows cast upon the photographic plate by (1) the passing bullet, (2) the sound waves, (3) irregular turbulences in the air, (4) grains of powder, etc. At the instant the bullet was passing before the photographic plate in a perfectly dark room a brilliant electric spark was produced, thus causing an instantaneous shadow. The bullets shown are .30-caliber service projectiles fired from a Springfield rifle, the duration of the electric spark being 1/500,000 of a second. To the extreme left is the tip of the muzzle of the rifle, and in the midst of the black cloud of powder particles is faintly seen the bullet, actually $1\frac{1}{2}$ inches in front of the muzzle and traveling with a speed of 2700 feet per second. The faint spherical sound wave seen ahead of the mushroom-shaped body of gas is a compressional wave started in the barrel by the movement of the bullet in leaving its cartridge case. The black area in front of the bullet represents gases that leaked past the bullet and got out ahead of it, and that behind it consists of propelling gases. The smaller but more intense sound wave is the chief cause of the report of the rifle. The picture to the right is a rifle bullet after passing through a soap bubble filled with a mixture of air and hydrogen, through which sound travels with a speed of 3200 feet per second, or 500 feet per second faster than the bullet. From an inspection of this picture it will be seen how both the head and base waves of the bullet have been modified in shape by the high velocity of sound in the air-hydrogen mixture. (See § 482)

twice the curvature of the mirror, or $1/f = 2 \times 1/R$; hence $f = R/2$. In other words, *the focal length of a mirror is equal to one half its radius.*

447. Image of an object in a convex mirror. We are all familiar with the fact that a convex mirror always forms behind the mirror a virtual, erect, and diminished image. The reason for this is shown clearly in Fig. 427. The image of the point P lies, as in plane mirrors (see § 444), always on the perpendicular to the mirror, but now necessarily nearer to the mirror than the focus F, since, as the point P is moved from a position very close to the mirror, where its image is just behind it, out to an infinite distance, its image moves back only to the focal plane through F. Hence the image must lie somewhere between F and the mirror. The image $P'Q'$ of an object PQ is always diminished, because it lies between the converging lines PC and QC. It can be located by the ray method (Fig. 427) exactly as in the case of concave lenses. In fact, a convex mirror and a concave lens have exactly the same optical properties. This is because *each always increases the curvature of the incident waves by an amount $1/f$.*

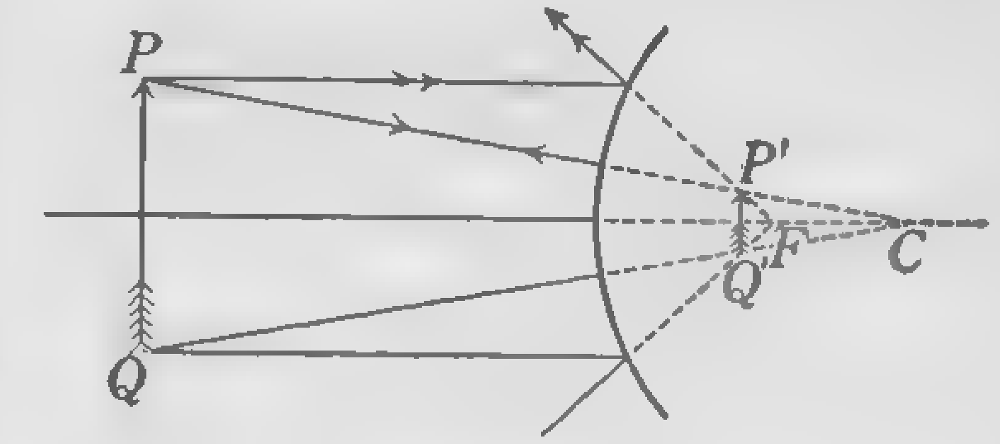


FIG. 427

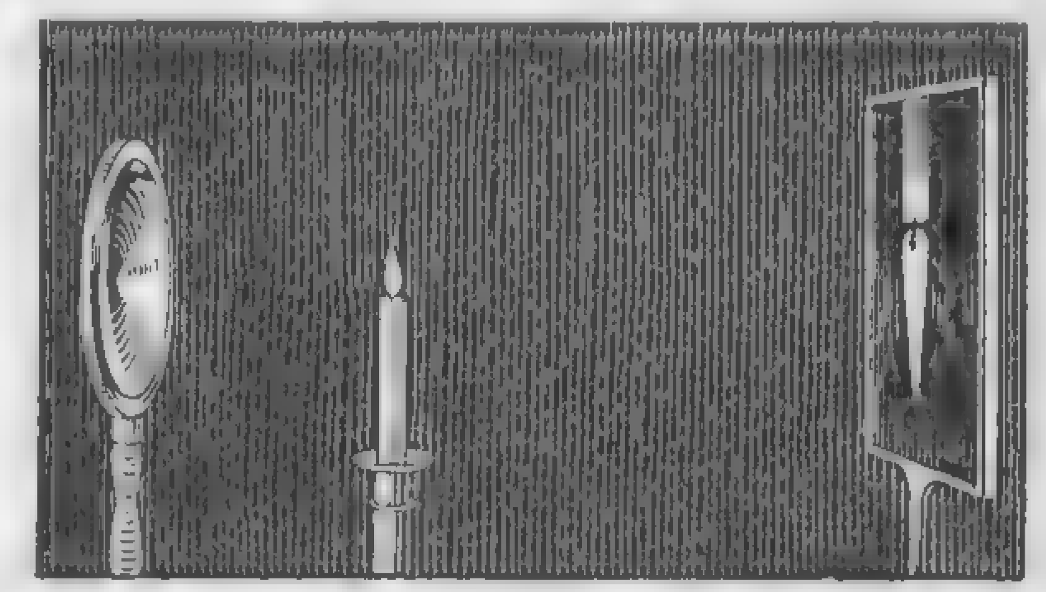


FIG. 428. Real image of candle formed by a concave mirror

448. Images in concave mirrors. Let the images obtainable with a concave mirror be studied precisely as were those obtainable from a convex lens. It will be found that exactly the same series of images is obtained: when the object is between the mirror and the principal focus, the image is virtual, enlarged, and erect; when it is at the focus, the reflected waves are plane, that

is, the rays from each point are a parallel bundle; when it is between the principal focus and the center of curvature, the image is inverted, enlarged, and real (Figs. 428 and 429); when

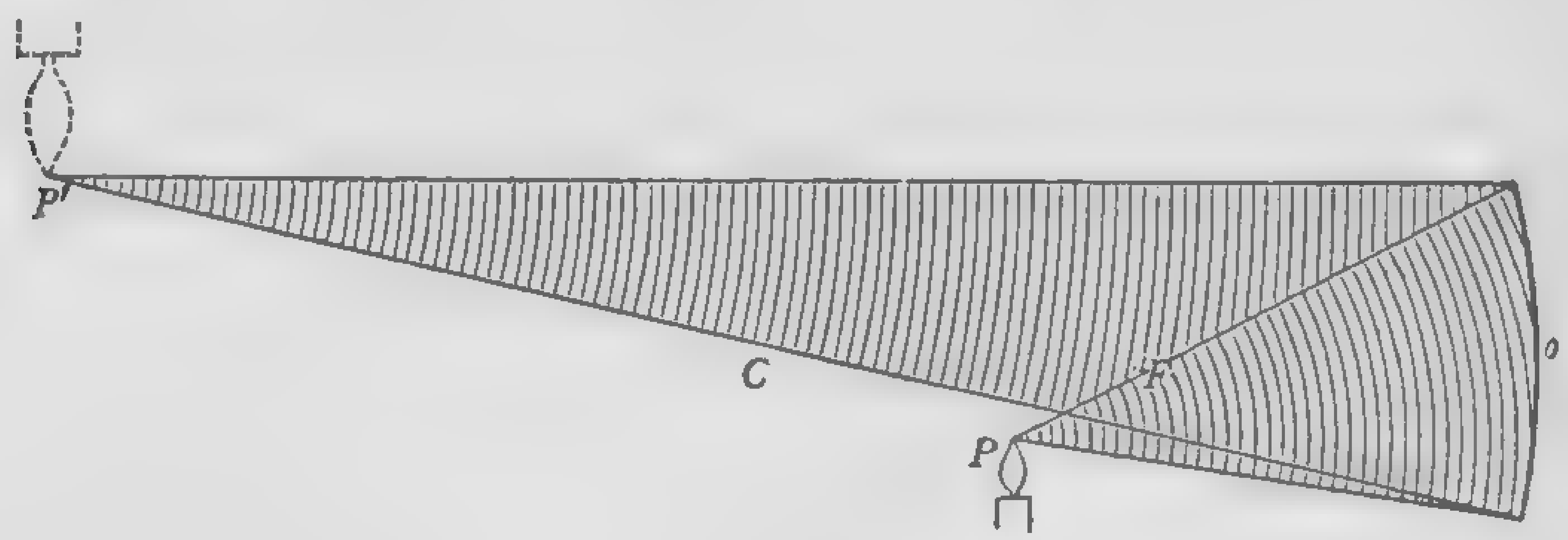


FIG. 429. Method of formation of a real image by a concave mirror

it is at a distance $R (= oC)$ from the mirror, the image is also at a distance R and of the same size as the object, though inverted; when the object is moved from R out to a great distance, the image moves from C up to F, and is always real, inverted, and diminished. The most convenient way of finding the focal length is to find where the image of a distant object is formed.

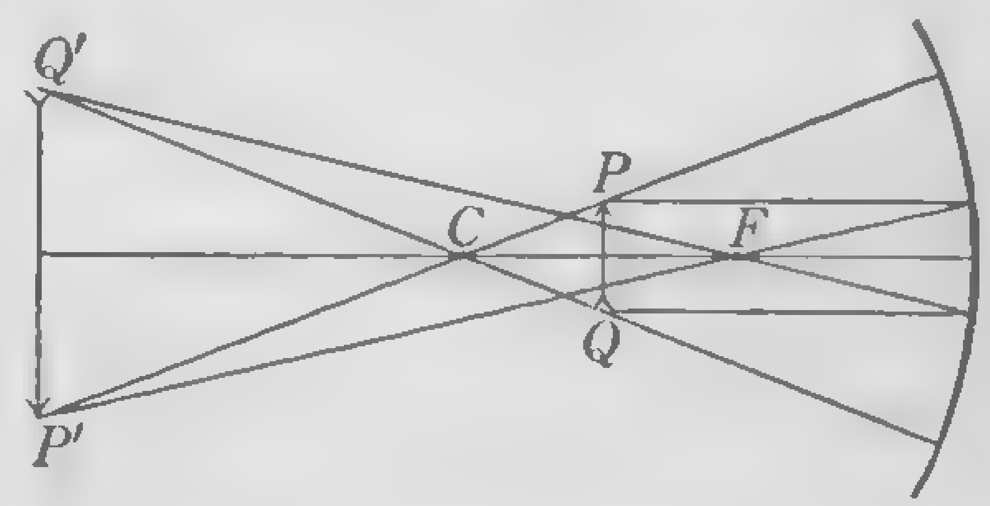


FIG. 430. Ray method of locating real image in a concave mirror

We learn, then, that a concave mirror has exactly the optical properties of a convex lens. This is because, like the convex lens, it always *diminishes* the curvature of the waves. The same formulas hold throughout, and the same constructions are applicable (see Fig. 430).*

SUMMARY. Concave mirrors and convex lenses have the same optical properties (see formulas, p. 414).

Convex mirrors and concave lenses have the same optical properties (see formulas, p. 414).

* Laboratory experiments on the formation of images by concave mirrors should follow this discussion. See, for example, Experiment 59 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

QUESTIONS AND PROBLEMS

1. Describe the image formed by a plane mirror.

2. Show by a diagram why the image of trees on the opposite side of a still lake appear inverted in the water.

3. A man is standing squarely in front of a plane mirror which is very much taller than he is. The mirror is tipped toward him until it makes an angle of 45° with the horizontal. He still sees his full length. What position does his image occupy?

4. Show from a construction of the image that a man cannot see his entire length in a vertical mirror unless the mirror is half as tall as he is. Decide from a study of the figure whether or not the distance of the man from the mirror affects the case.

5. Describe the image formed by a convex mirror. Why can it never be larger than the object?

6. Can a convex mirror ever form an inverted image? Why?

7. Why does the nose appear relatively large in comparison with the ears when the face is viewed in a convex mirror?

8. When does a concave mirror form a real image? a virtual image? When an enlarged image? a diminished image? When an erect image? an inverted image?

9. An object 5 cm. long is 50 cm. from a concave mirror of focal length 30 cm. Where is the image, and what is its size?

10. A candle placed 20 cm. in front of a concave mirror has its image formed 50 cm. in front of the mirror. Find the radius of the mirror.

OPTICAL INSTRUMENTS

449. The photographic camera. A fairly distinct, though dim, image of a candle flame can be obtained with nothing more elaborate than a pinhole in a piece of cardboard (Fig. 431). If the receiving screen is replaced by a photographic plate, the arrangement becomes a *pinhole camera,* with which good pictures may be taken if the exposure is

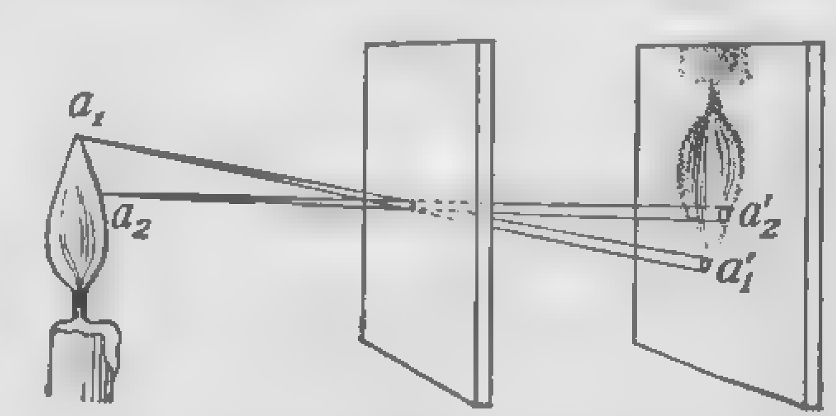


FIG. 431. Image formed by a small opening

sufficiently long. If we try to increase the brightness of the image by enlarging the hole, the image becomes blurred, because the narrow pencils $a_1a'_1$, $a_2a'_2$, etc. become cones whose bases a'_1, a'_2, overlap and thus destroy the distinctness of the outline.

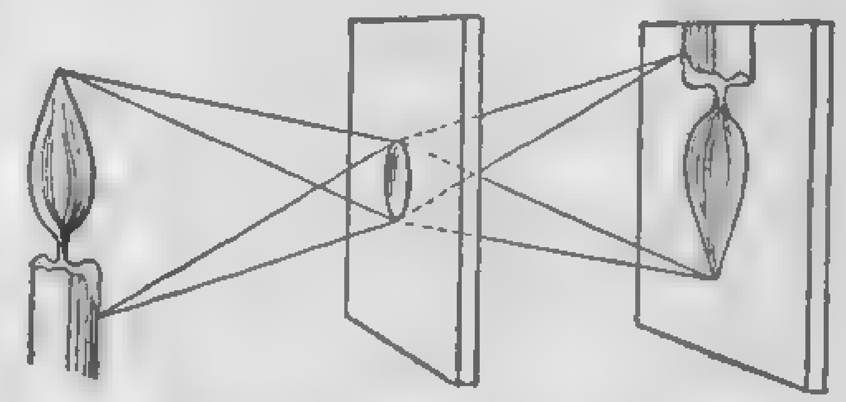


FIG. 432. Principle of the photographic camera

It is possible, without sacrificing distinctness of outline, to gain the increased brightness due to the larger hole by placing a lens in the hole (Fig. 432). If the receiving screen is now a sensitive plate, the arrangement becomes a *photographic camera* (Fig. 433). But whereas with the pinhole camera the screen may be at any distance from the hole, with a lens the plate and the object must be at conjugate foci of the lens.

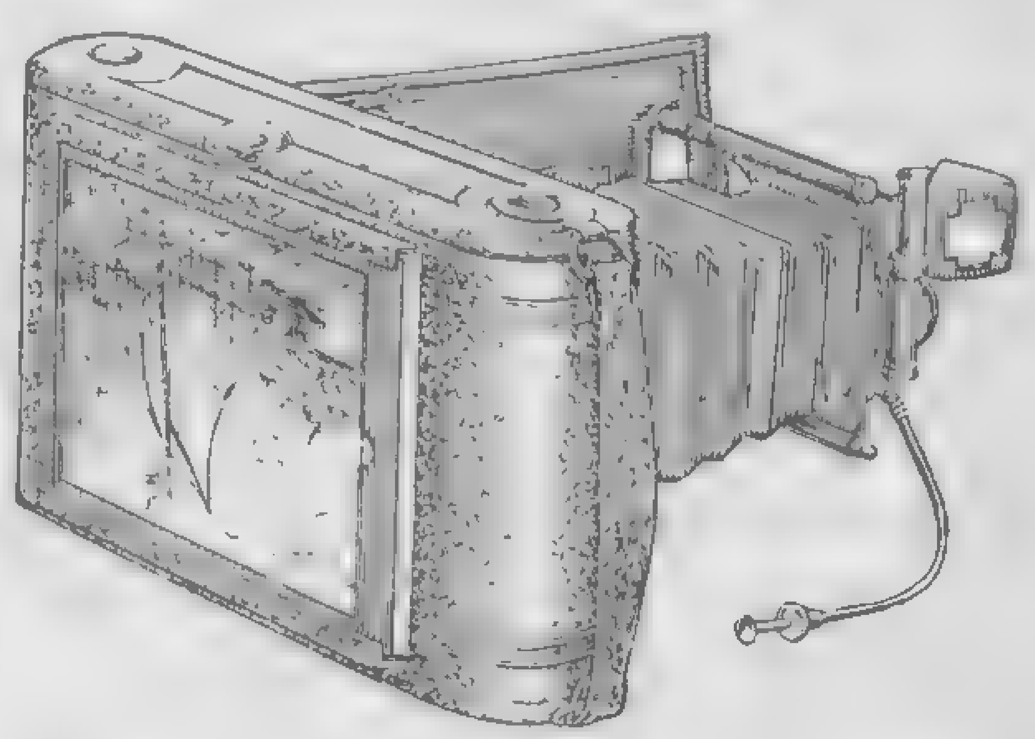


FIG. 433. The photographic camera

Let a lens of, say, 4 ft. focal length be placed in front of a hole in the shutter of a darkened room, and a semitransparent screen (for example, architect's tracing paper) placed at the focal plane. A perfect reproduction of the opposite landscape will appear.

450. The projecting lantern. The projecting lantern is essentially a camera in which the position of object and image have been interchanged; for in the use of the camera the object is at a considerable distance, and a small inverted image is formed on a plate placed somewhat farther from the lens than the focal distance. In the use of the projecting lantern the object P (Fig. 434) is placed a trifle farther from the lens L' than its focal length, and an enlarged inverted image is formed on a distant screen S. In both instruments the optical part is a combination of lenses equivalent to a convex lens.

The object P, whose image is formed on the screen, is usually a transparent slide which is illuminated by a powerful light A. The image is as many times larger than the object as the distance from L' to S is greater than the distance from

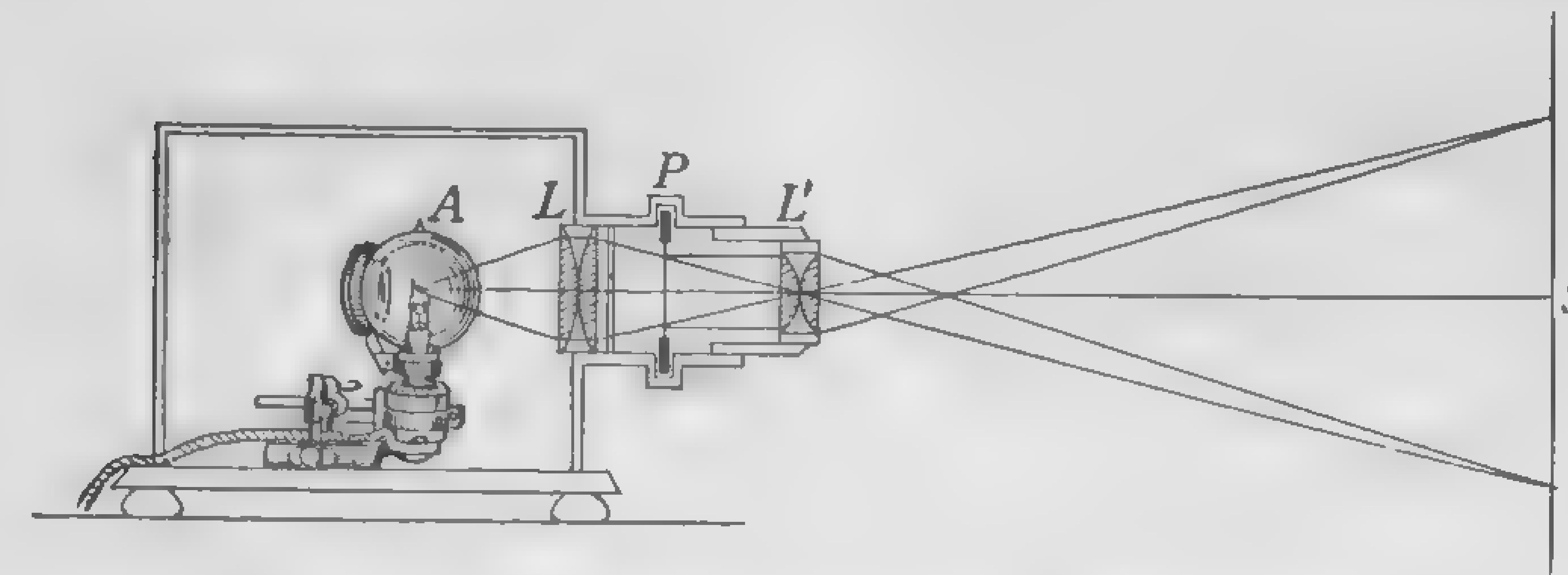


FIG. 434. The projecting lantern (stereopticon)

L' to P. The light A is usually either an incandescent lamp or an electric arc. The moving-picture projector employs a long film of small "positives" which moves swiftly between the condensing lens L and the projecting lens L' (see frontispiece and opposite page 418).

The above are the only essential parts of a projecting lantern. In order, however, that the slide may be illuminated as brilliantly as possible, a so-called condensing lens L is always used. This concentrates light upon the transparency and directs it toward the screen.

In order to illustrate the principle of the instrument, let a beam of sunlight be reflected into the room and fall upon a lantern slide. When a lens is placed a trifle more than its focal distance in front of the slide, a brilliant picture will be formed on the opposite wall.

451. The eye. The eye is essentially a camera in which the cornea C (Fig. 435), the aqueous humor l, and the crystalline lens o act as one single lens which forms an inverted image $P'Q'$ on the retina, an expansion of the optic nerve covering the inside of the back of the eyeball.

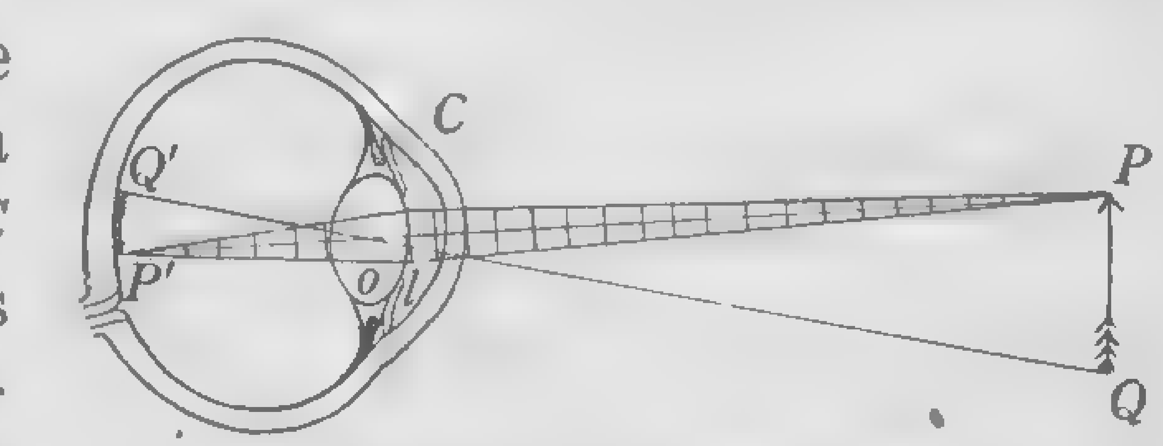


FIG. 435. The human eye

In the case of the camera the images of objects at different distances are obtained by placing the plate nearer to the lens

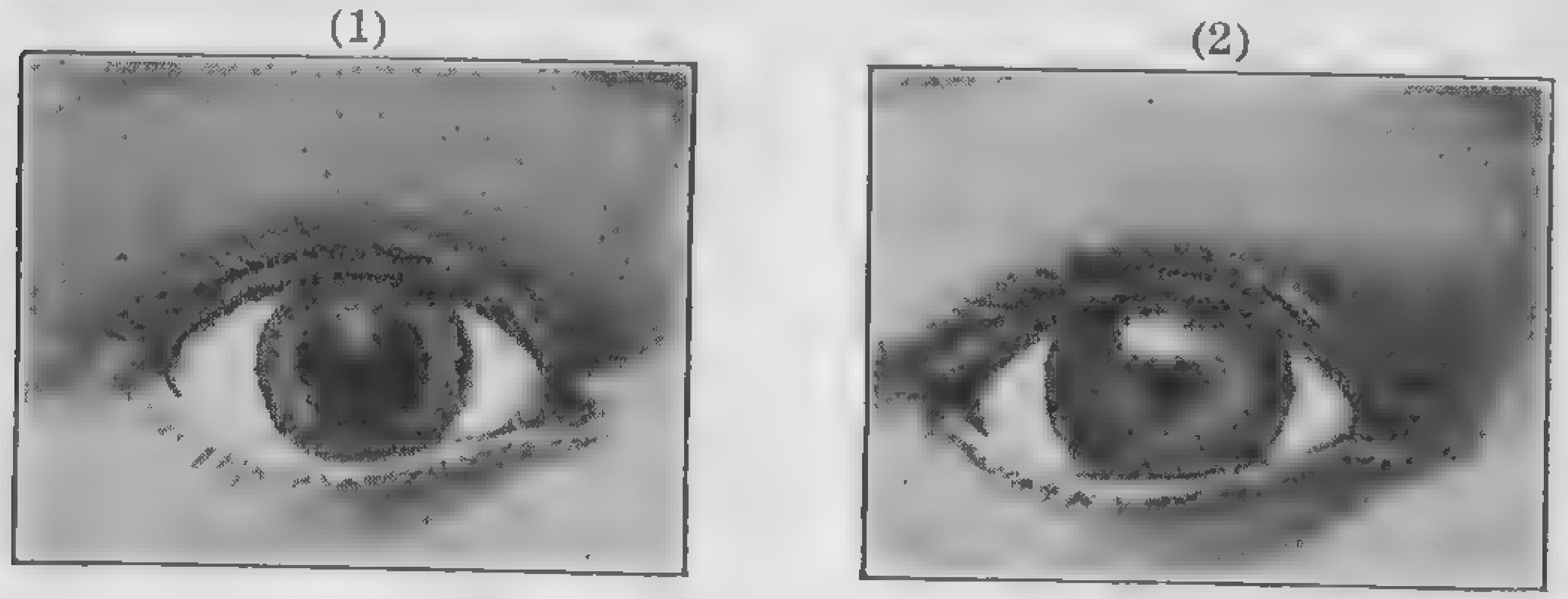


FIG. 436. The pupil dilates when the light is dim and contracts when it is intense

or farther from it. In the eye, however, the distance from the retina to the lens remains constant, and the adjustment for different distances is effected by changing the focal length of the lens system in such a way as always to keep the image upon the retina. Thus, when the normal eye is perfectly relaxed, the lens has just the proper curvature to focus plane waves upon the retina, that is, to make distant objects distinctly visible. But by directing attention upon objects close by we cause the muscles which hold the lens in place to contract in such a way as to make the lens more convex, and thus bring into distinct focus objects which may be as close as eight or ten inches. This power of adjustment, or *accommodation*, however, varies greatly in different individuals.

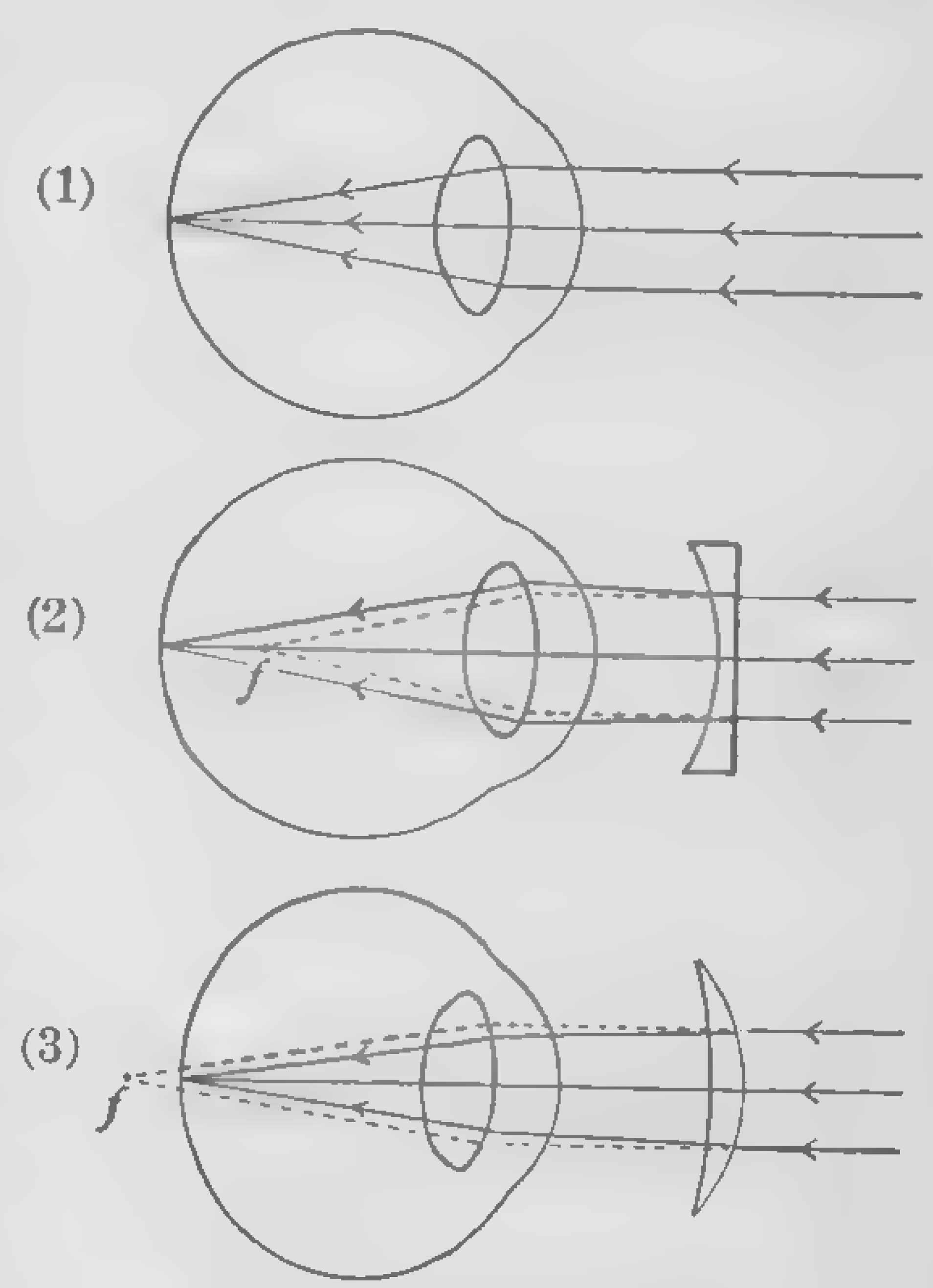


FIG. 437. Defects of vision

The iris, or colored part of the eye, is a diaphragm which varies the amount of light which is admitted to the retina (Figs. 436 (1) and (2)).

452. Nearsightedness and farsightedness. In a *normal* eye, provided the lens is relaxed and resting, parallel rays come to a focus *on* the retina (Fig. 437 (1)); in a *nearsighted* eye they focus *in front of* the retina (Fig. 437 (2)); and in a *farsighted* eye they reach the retina *before coming to a focus* (Fig. 437 (3)).

Those who are nearsighted can see distinctly only those objects which are near. The usual reason for nearsightedness is that the retina is too far from the lens. The diverging lens corrects this defect of vision because it makes the rays from a distant object enter the eye as if they had come from an object near by; that is, it partially counteracts the converging effect of the eye (Fig. 437 (2)).

Those who are farsighted cannot see distinctly even a very distant object *when the lens is relaxed.* The usual reason for farsightedness is that the eyeball is too short from lens to retina. The rays from *near* objects are converged, or focused, towards f behind the retina in spite of all effort at accommodation. A converging lens gives distinct vision because it supplements the converging effect of the eye (Fig. 437 (3)). In old age the lens loses its power of accommodation, that is, the ability to become more convex when looking at a near object; hence, in old age a normal eye requires the same sort of lens as is used in true farsightedness.

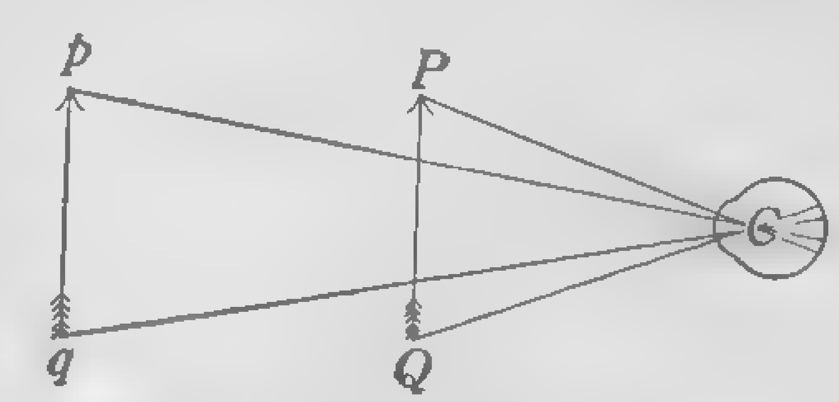


FIG. 438. The visual angle

453. The apparent size of a body. The apparent size of a body depends simply upon the size of the image formed upon the retina by the lens of the eye, and hence upon the size of *the visual angle pCq* (Fig. 438). The size of this angle evidently increases as the object is brought nearer to the eye (see *PCQ*). Thus, the image formed on the retina when a

man is one hundred feet from the eye is in reality only one tenth as large as the image formed of the same man when he is but ten feet away. We do not actually interpret the larger image as representing a larger man simply because we have been taught by lifelong experience to take account of the known distance of an object in forming our estimate of its actual size. To an infant who has not yet formed ideas of distance the man ten feet away doubtless appears ten times as large as the man one hundred feet away.

454. Distance of most distinct vision. When we wish to examine an object minutely, we bring it as close to the eye as possible in order to increase the size of the image on the retina. But there is a limit to the size of the image which can be produced in this way; for when the object is brought nearer to the normal eye than about 10 inches, the curvature of the incident wave becomes so great that the eye lens is no longer able, without too much strain, to thicken sufficiently to bring the image into sharp focus upon the retina. Hence a person with normal eyes holds an object which he wishes to see as distinctly as possible at a distance of about 10 inches.

Although this so-called *distance of most distinct vision* varies somewhat with different people, for the sake of having a standard of comparison in the determination of the magnifying powers of optical instruments some exact distance had to be chosen. The distance so chosen is 10 inches, or 25 centimeters.

455. Magnifying power of a convex lens. If a convex lens is placed immediately before the eye, the object may be brought much closer than 25 centimeters without loss of distinctness, for the curvature of the wave is partly or even wholly overcome by the lens before the light enters the eye.

If we wish to use a lens as a magnifying glass to the best advantage, we place the eye *as close to it as we can*, so as to gather as large a cone of rays as possible, and then place the object at a distance from the lens *equal to its focal length*, so that the waves after passing through it are plane. They are

then focused by the eye with the least possible effort. The visual angle in such a case is PcQ (Fig. 439 (1)); for, since the emergent waves are plane, the rays which pass through the center of the eye from P and Q are parallel to the lines through Pc and Qc. But if the lens were not present, and if the object were 25 centimeters from the eye, the visual angle would be the small angle pcq (Fig. 439 (2)). *The magnifying power of a simple lens is due, therefore, to the fact that by its use an object can be viewed distinctly when held closer to the eye than is otherwise possible. This condition gives a visual angle that increases the size of the image on the retina.* The less the focal length of the lens, the nearer to it may the object be placed, and therefore the greater the visual angle, or magnifying power.

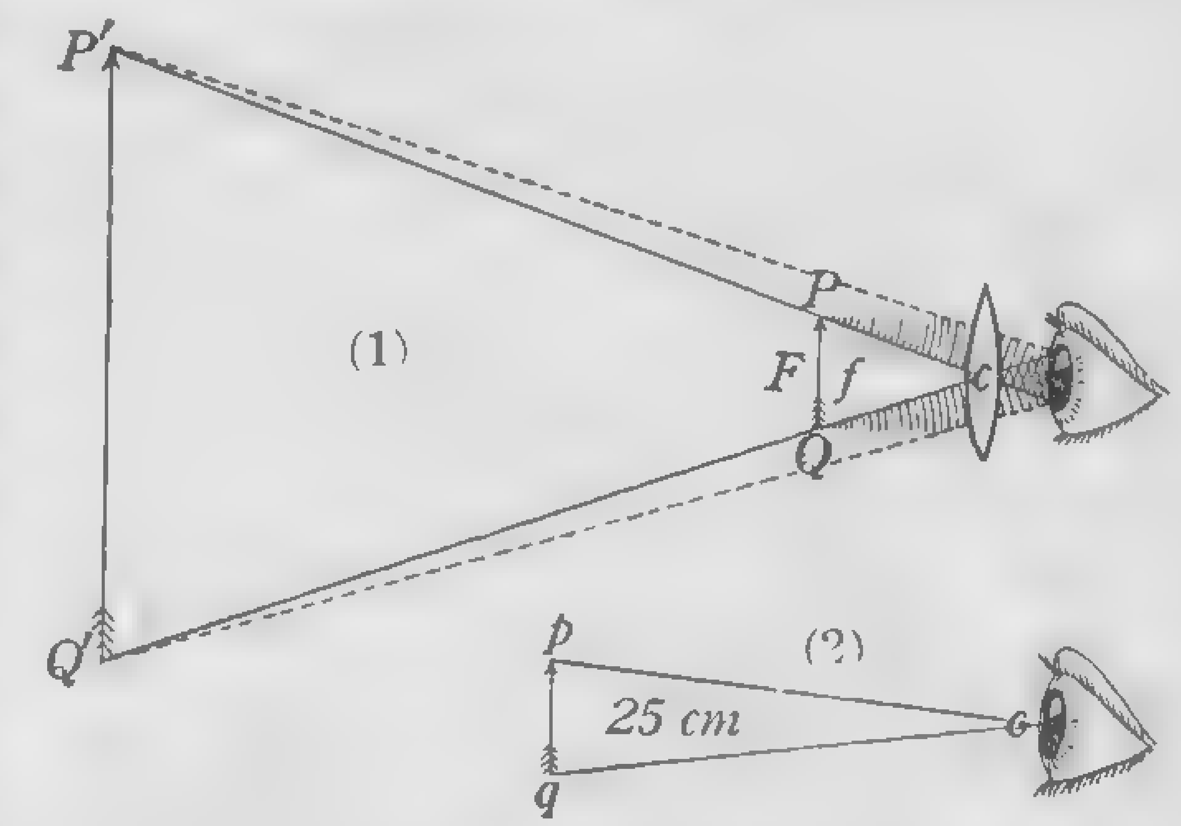


FIG. 439. Magnifying power of a lens

The ratio of the two angles PcQ and pcq is approximately $25/f$, where f is the focal length of the lens expressed in centimeters. Now *the magnifying power of a lens or microscope is defined as the ratio of the angle actually subtended by the image when viewed through the instrument, to the angle subtended by the object when viewed with the unaided eye at a distance of 25 centimeters.* Therefore the magnifying power of a simple lens is $25/f$. Thus, if a lens has a focal length of 2.5 centimeters, it produces a magnification of 10 diameters when the object is placed at its principal focus. If the lens has a focal length of 1 centimeter, its magnifying power is 25, etc.

456. Magnifying power of an astronomical telescope. In the astronomical telescope the *objective*, or forward lens, forms *at its principal focus* an image $P'Q'$ of an object PQ which is usually very distant. This image may be viewed by the unaided eye at a

distance of 25 cm. (Fig. 440). The visual angle when the very distant object is viewed with the unaided eye is PoQ, whereas with the objective, whose focal length is usually very much longer than 25 cm. (about 2000 cm. in the case of the great Yerkes telescope), the visual angle $P'EQ'$ is much greater than PoQ, so that the visual angle is increased by means of the objective alone. In

FIG. 440. The magnifying power of a telescope objective is $F/25$

practice, however, this image is not viewed by the unaided eye, but is increased several times more with a simple short-focus magnifying glass called an *eyepiece* (Fig. 441) placed so that the image is at its focus.

The increase in the visual angle $P'EQ'$ (Fig. 440) through the use of the objective alone is in direct proportion to its focal length, the increase being $F/25$. This becomes obvious from the following consideration. The angle PoQ = angle $P'oQ'$. Regarding the short line $Q'P'$ as an arc, we see that the angles $Q'EP'$ and $Q'oP'$ (= PoQ) are inversely proportional to their radii; that is, visual angle with objective : visual angle without objective :: focal length of objective : 25. The magnifying power of the objective alone is, therefore, $F/25$. In the case of the Yerkes telescope this increase is $2000/25 = 80$ times.

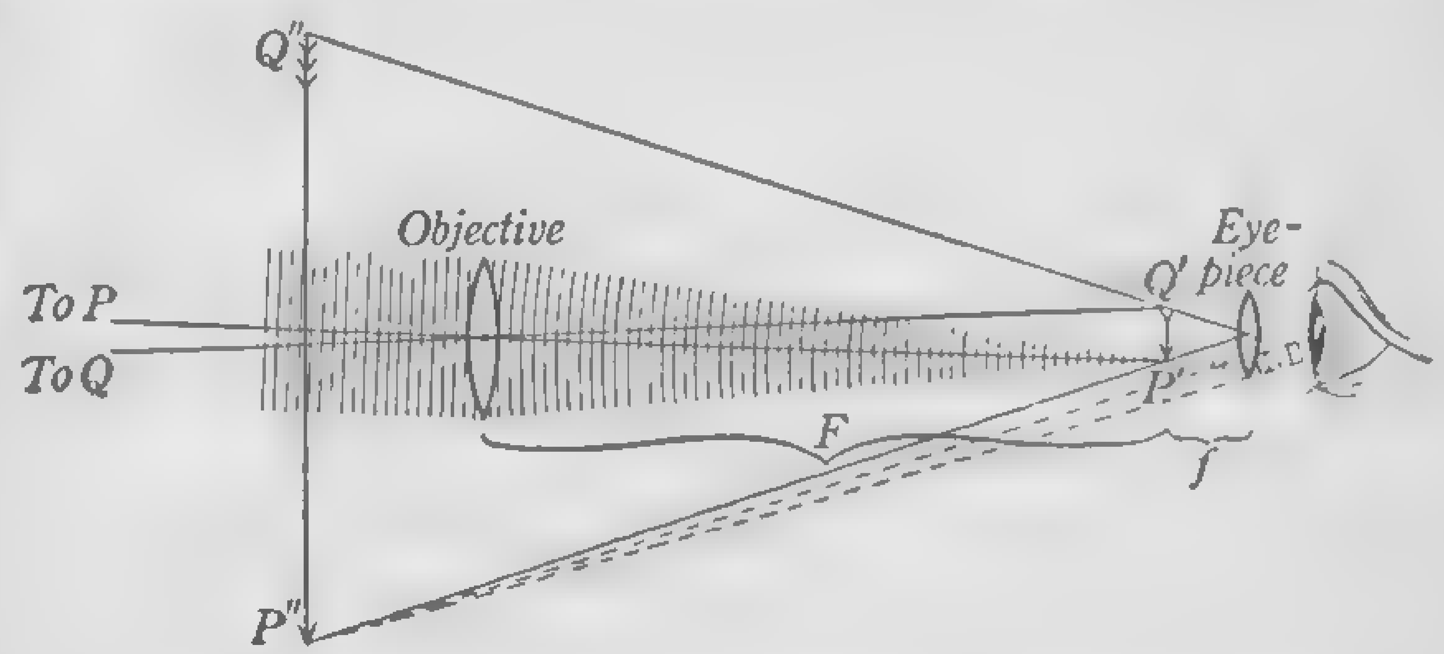
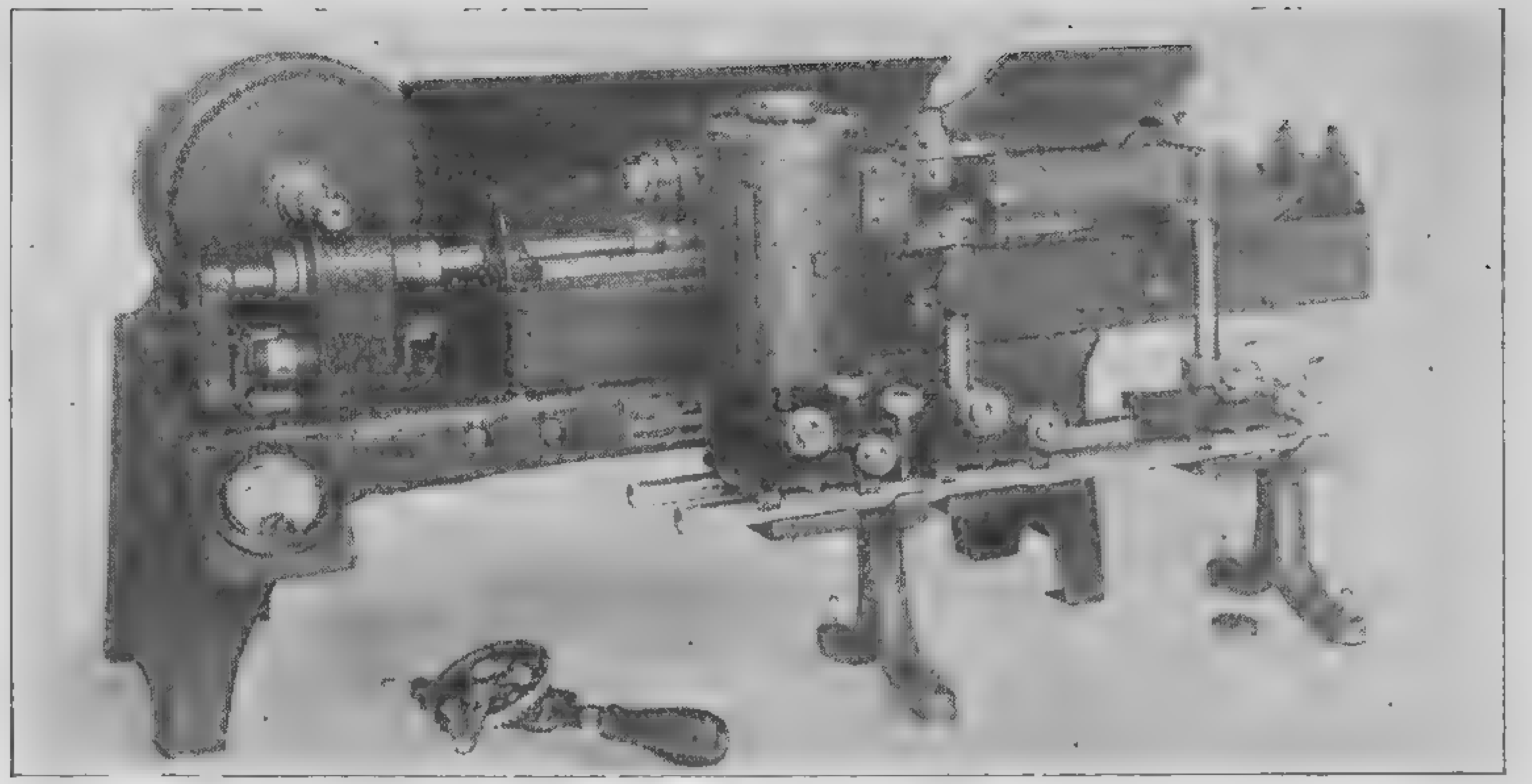


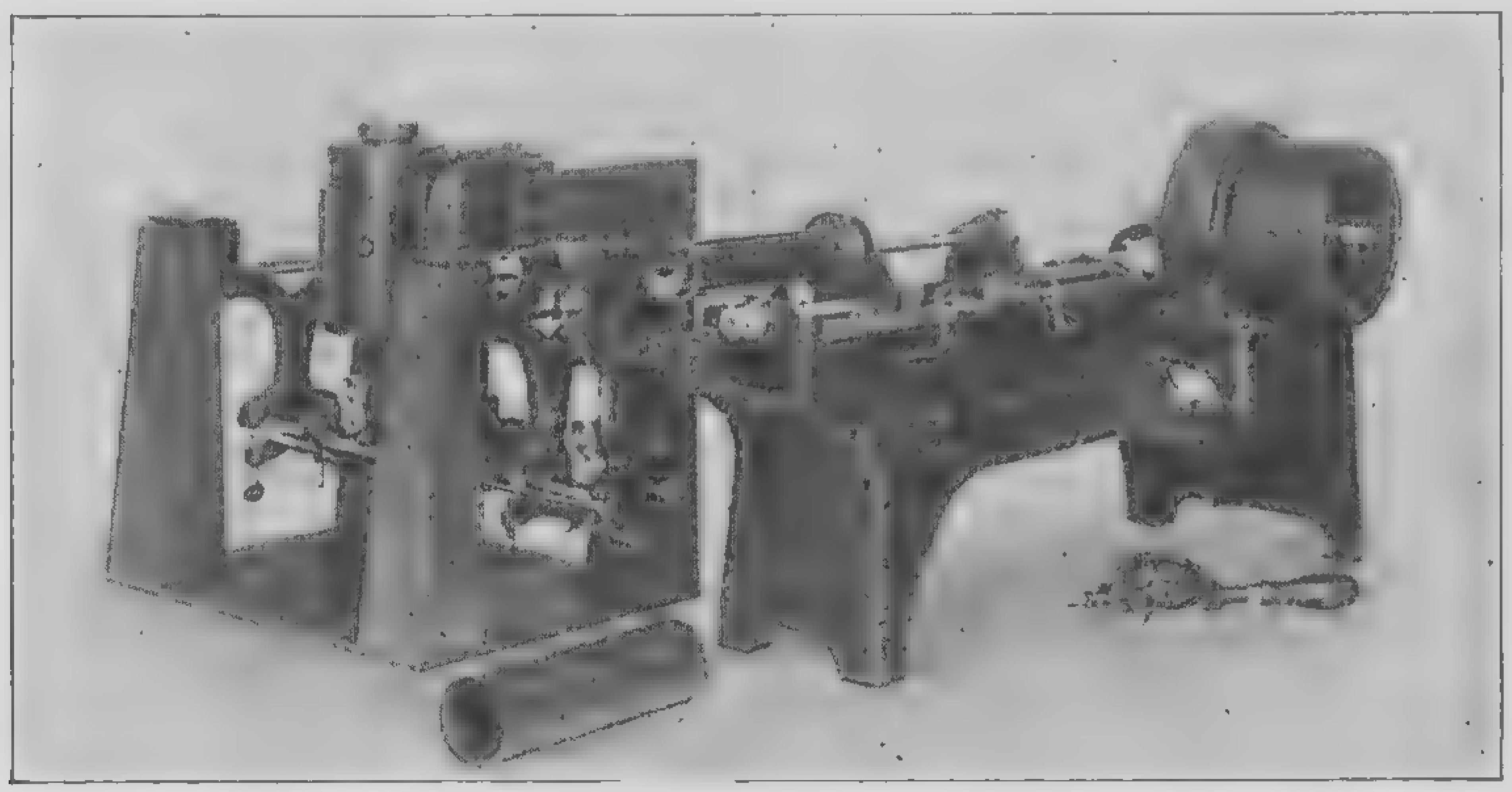
FIG. 441. The magnifying power of a telescope is F/f

Since we have seen in § 455 that the simple magnifying glass increases the visual angle $25/f$ times, f being the focal length of the eyepiece, it is clear that the total magnification produced by both lenses, used as above, is $F/25 \times 25/f = F/f$. *The magnifying power of an astronomical telescope is therefore the focal length of the objective divided by the focal length of the eyepiece.* It will be seen,

ALEXANDER GRAHAM BELL (1847–1922)

This portrait of the inventor of the telephone was transmitted 3305 miles over the wire and reproduced by the aid of the photoelectric cell, a device embodying the latest knowledge of the properties of the electron. (See following page)





TRANSMISSION OF PICTURES BY WIRE

The transmitting apparatus is shown above; the receiving, below. The picture, finger prints, writing, etc. to be transmitted are on a transparent film wrapped around a horizontal cylinder behind the centrally located lamp. A motor at the left rotates the cylinder and at the same time advances it .01 inch during each revolution. A small beam of light passing through the film and falling upon a photoelectric cell causes current changes proportional to the light received by the cell. At the receiving end the variable incoming current controls the intensity of a small beam of light falling upon a rotating and advancing film. Thus a picture is built up by light variations corresponding to those falling upon the photoelectric cell at the transmitter. A 400-cycle current passing over the telephone wire perfectly synchronizes the motors at the two ends of the line (see previous page). (Courtesy of the Western Electric Company)

therefore, that to get a high magnifying power it is necessary to use an objective of as great focal length as possible and an eyepiece of as short focal length as possible. The focal length of the lens at the Yerkes Observatory is about 62 feet, and its diameter 40 inches. The great diameter enables it to collect a very large amount of light, which makes celestial objects more plainly visible.

Eyepieces often have focal lengths as small as $\frac{1}{4}$ inch. Thus, the Yerkes telescope, when used with a $\frac{1}{4}$-inch eyepiece, has a magnifying power of 2976.

457. The magnifying power of the compound microscope. The compound microscope is like the telescope in that the front lens, or *objective*, forms a real image of the object at the focus of the eyepiece. The size of the image $P'Q'$ (Fig. 442) formed by the objective is as many times the size of the object PQ as D_i, the distance from the objective to the image, is times D_o, the distance from the objective to the object (see § 441). Since the eyepiece magnifies this image $25/f$ times, the total magnifying power of a compound microscope is $D_i/D_o \times 25/f$. Ordinarily D_i is practically the length L of the microscope tube, and D_o is the focal length F of the objective. Wherever this is the case, then, the magnifying power of the compound microscope is $25\ L/Ff$.

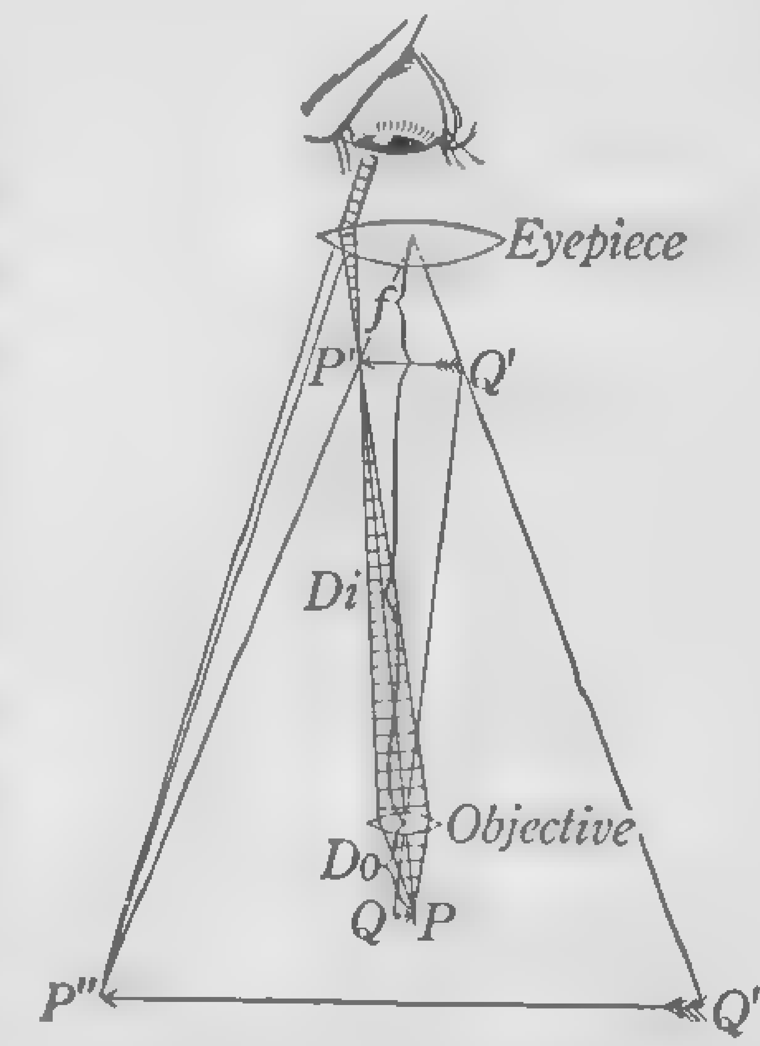


FIG. 442. The compound microscope

The relation shows that in order to get a high magnifying power with a compound microscope the focal length of both eyepiece and objective should be as short as possible, whereas the tube length should be as long as possible. Thus, if a microscope has both an eyepiece and an objective of 6 millimeters focal length and a tube 15 centimeters long, its magnifying power will be

$$\frac{25 \times 15}{.6 \times .6} = 1042.$$

Magnifications as high as 2500 or 3000 are sometimes used, but it is impossible to go much farther, for the reason that the image becomes too faint to be seen when it is spread over so large an area.

458. The opera glass. On account of the large number of lenses which must be used in a terrestrial telescope, it is too bulky and awkward for many purposes, and hence it is often replaced by the opera glass (Fig. 443). This instrument consists of an objective like that of the telescope, and an eyepiece which is a concave lens of the same focal length as the eye of the observer. The effect of the eyepiece is therefore to neutralize the lens of the eye. Hence the objective, in effect, forms its image directly upon the retina. This means that the angle of vision $P'cQ'$ ($= P''cQ''$) obtained through the use of the opera glass is as many times the angle of vision PCQ ($= P''CQ''$) for the unaided eye as the focal length CR of the objective is times the focal length cR of the eye; that is, the size of the image formed upon the retina

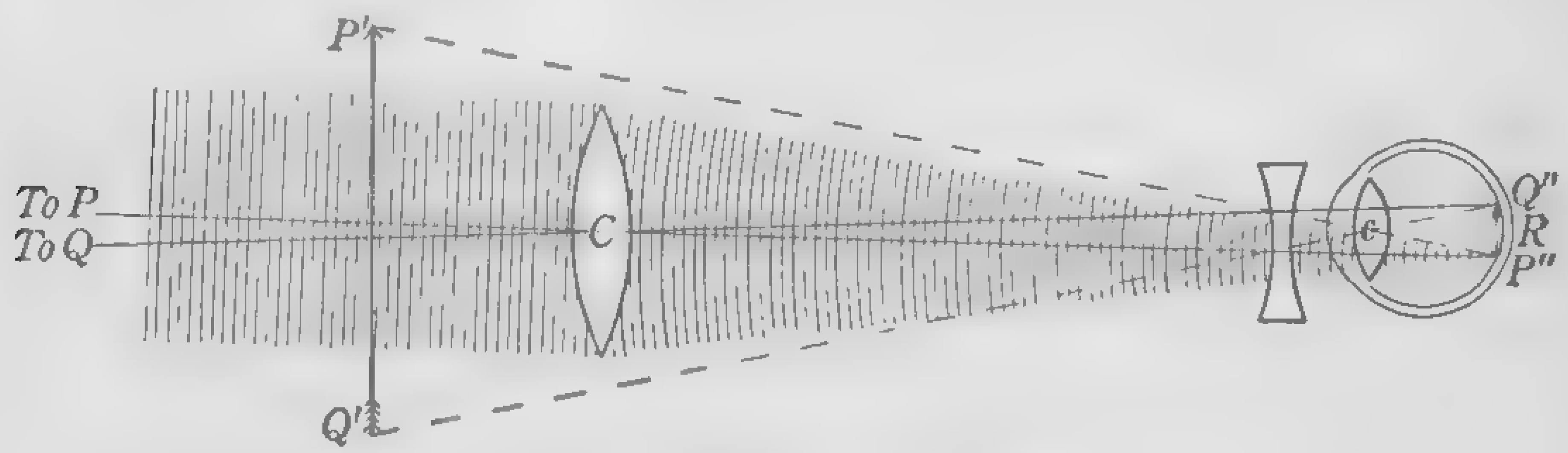


FIG. 443. The opera glass

by the objective is as many times as large as that formed *by the unaided eye* as CR is times cR. Since the focal length of the eye is the same as that of the eyepiece, *the magnifying power of the opera glass, like that of the astronomical telescope, is the ratio of the focal lengths of the objective and eyepiece.* Objects seen with an opera glass appear erect, since the image formed on the retina is inverted, as is the case with images formed by the lens of the eye unaided.

459. The stereoscope; binocular vision. When an object is seen with both eyes, the images formed on the two retinas differ slightly, because of the fact that the two eyes, on account of their lateral separation, are viewing the object from slightly different angles. It is this difference in the two images which gives to an object or landscape viewed with two eyes an appearance of depth, or solidity, which is wholly wanting when one eye is closed. The stereoscope is an instrument which reproduces in photographs this effect of binocular vision. Two photographs of the same object are taken from slightly different points of view. These

photographs are mounted at A and B (Fig. 444), where they are simultaneously viewed by the two eyes through the two prismatic lenses m and n. These two lenses superpose the two images at C because of their action as prisms, and at the same time magnify them because of their action as simple magnifying lenses. The result is that the observer is conscious of viewing but one photograph; but this differs from ordinary photographs in that, instead of being flat, it has all the characteristics of an object actually seen with both eyes.

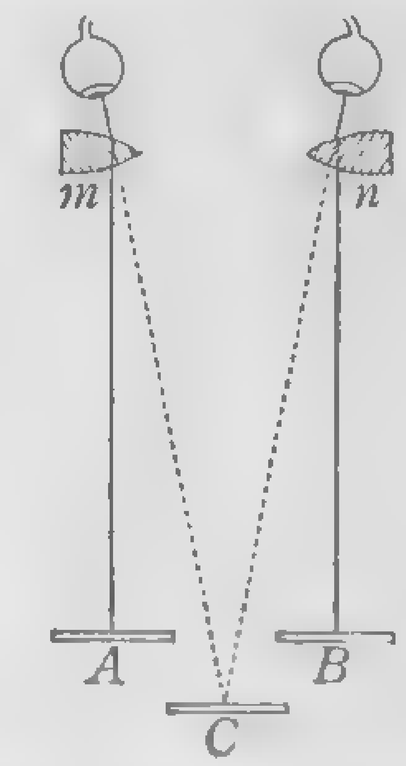


FIG. 444. Principle of the stereoscope

The opera glass has the advantage over the terrestrial telescope of affording the benefit of binocular vision; for whereas telescopes are usually constructed with one tube, opera glasses always have two, one for each eye.

460. The prism binocular. The greatest disadvantage of the opera glass is that the field of view is very small. The terrestrial telescope has a larger field but is of inconvenient length. An instrument called the prism binocular (Fig. 445) has recently come into use, which combines the compactness of the opera glass with the wide field of view of the terrestrial telescope. The compactness is gained by causing the light to pass back and forth through total-reflecting prisms, as in the figure. These reflections also perform the function of reinverting the image, so that the real image which is formed at the focus of the eyepiece is erect. It will be seen, therefore, that the instrument is essentially an astronomical telescope in which the image is reinverted by reflection and in which the tube is shortened by letting the light pass back and forth between the prisms.

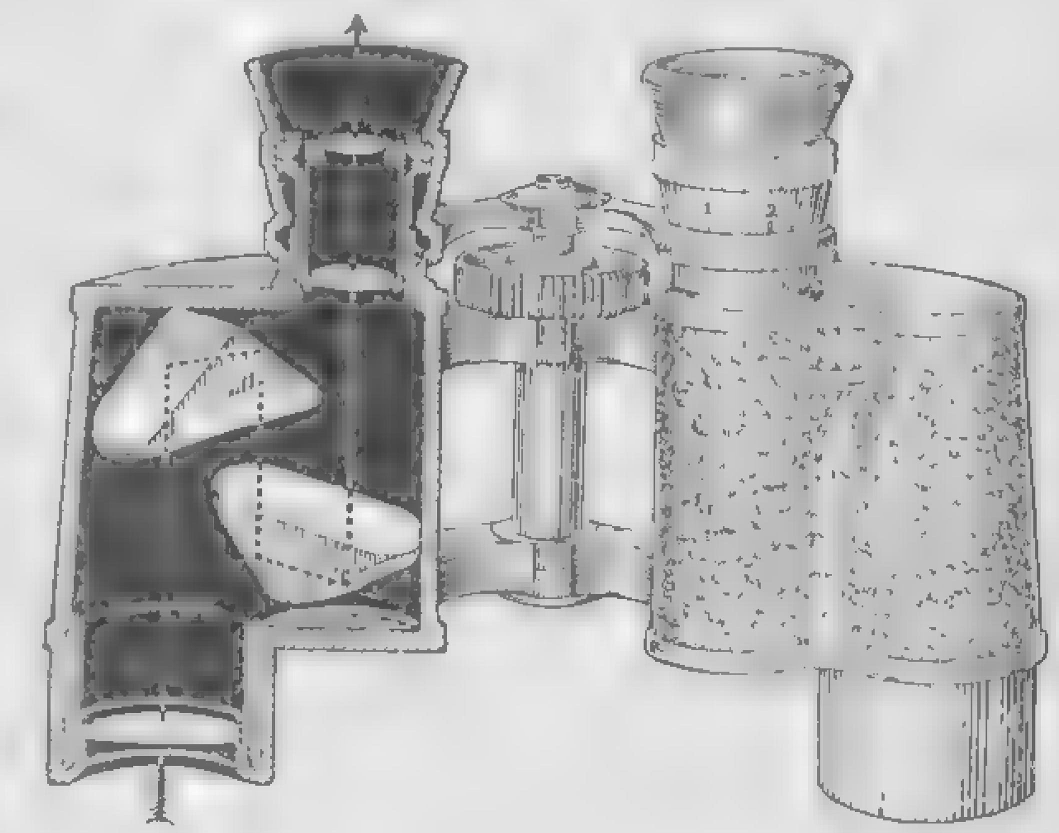


FIG. 445. The prism binocular

A further advantage which is gained by the prism binocular is due to the fact that the two objectives are separated by a distance

which is greater than the distance between the eyes; hence the stereoscopic effect is more prominent than with the unaided eye or with the ordinary opera glass.*

SUMMARY. The camera, the projection lantern, and the eye form real images on screens.

The magnifying power of the microscope, the telescope, the opera glass, and the field glass is due to the increase they produce in the visual angle.

The magnifying power of a single lens is considered equal to the ratio of 25 centimeters (or 10 inches) to the focal length of the lens.

The magnifying power of the telescope and of the opera glass is equal to the ratio of the focal length of the objective to that of the eyepiece.

The magnifying power of a compound microscope is the product of the magnifying power of the objective and that of the eyepiece.

QUESTIONS AND PROBLEMS†

1. If a pinhole camera is 8 in. long and the image of a building 50 ft. high appears as an image 3 in. high on the plate, how far away is the building?

2. How tall is a tree 200 ft. away if the image of it formed by a camera lens of focal length 4 in. is 1 in. long? (Consider the image to be formed in the *focal plane.*)

3. How long an image of the same tree will be formed in the focal plane of a lens having a focal length of 9 in.?

4. When a camera is adjusted to photograph a distant object, what change in the length of the bellows must be made to photograph a near object? Explain clearly why this adjustment is necessary.

5. From Fig. 446 explain the camera view finder, F being the principal focus of the objective and F' that of the eyepiece.

* Laboratory experiments on the magnifying powers of lenses and on the construction of microscopes and telescopes should follow this chapter. See, for example, Experiments 60, 61, and 62 of "Exercises in Laboratory Physics," by Millikan, Gale, and Davis.

† Supplementary questions and problems for Chapter XIX are given in the Appendix.

6. Explain why both near and distant objects can be satisfactorily photographed with a small fixed-focus camera.

7. The projection lens of a lantern has a focal length of 1 ft. How far back of the lens must a slide be placed in order to focus clearly upon the screen 24 ft. from the lantern?

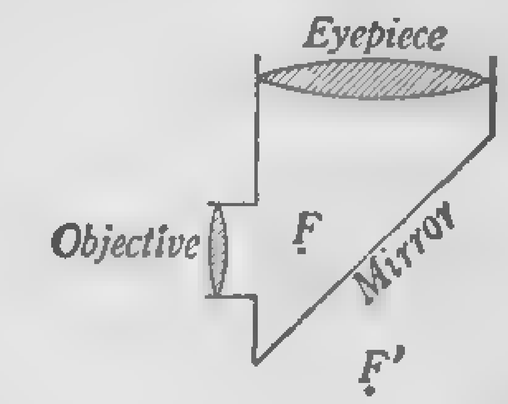


FIG. 446. View-finder of camera

8. Is the image on the retina erect or inverted?

9. Why is it necessary for the pupils of your eyes to be larger in a dim cellar than in the sunshine? Why does the photographer use a large stop on dull days in photographing moving objects?

10. What sort of lenses are necessary to correct nearsightedness? farsightedness? Explain with the aid of a diagram.

11. Given a spectacle lens, how could you determine whether it is a converging or a diverging lens?

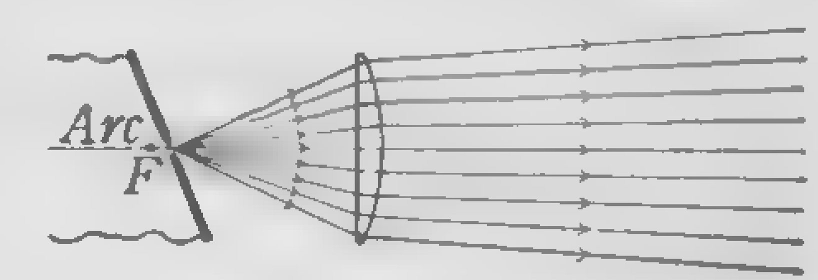


FIG. 447. Principle of the spotlight

12. What is the magnifying power of a $\frac{1}{4}$-inch lens used as a simple magnifier?

13. Fig. 447 represents a theater spotlight projector adjusted to illuminate a small part of the stage. How must the arc be moved to illuminate a larger area on the stage? (F is the principal focus of the plano-convex lens.)

14. A telescope has an objective whose focal length is 30 ft. and an eyepiece whose focal length is 1 in. What is the magnifying power of the telescope?

CHAPTER XX

COLOR PHENOMENA

Color and Wave Lengths

461. Wave lengths of different colors. Let a soap film be formed across the top of an ordinary drinking glass, care being taken that both the solution and the glass are as clean as possible. Let a beam of sunlight or the light from a projecting lantern pass through a piece of red glass at *A*, fall upon the soap film *F*, and be reflected from it to a white screen *S* (see Fig. 448). Let a convex lens *L* of from six to twelve inches focal length be placed in the path of the reflected beam in such a position as to produce an image of the film upon the screen *S*, that is, in such a position that film and screen are at conjugate foci of the lens. The system of red and black bands upon the screen is formed precisely as in § 428, by the interference of the two beams of light coming from the front and back surfaces of the wedge-shaped film. Now let the red glass be held in one half of the beam and a piece of green glass in the other half, the two pieces being placed edge to edge, as shown at *A*. Two sets of fringes will be seen side by side on the screen. The fringes will be red and black on one side of the image, and green and black on the other; but it will be noticed at once that the dark bands on the green side are closer together than the dark bands on the other side; in fact, seven fringes on

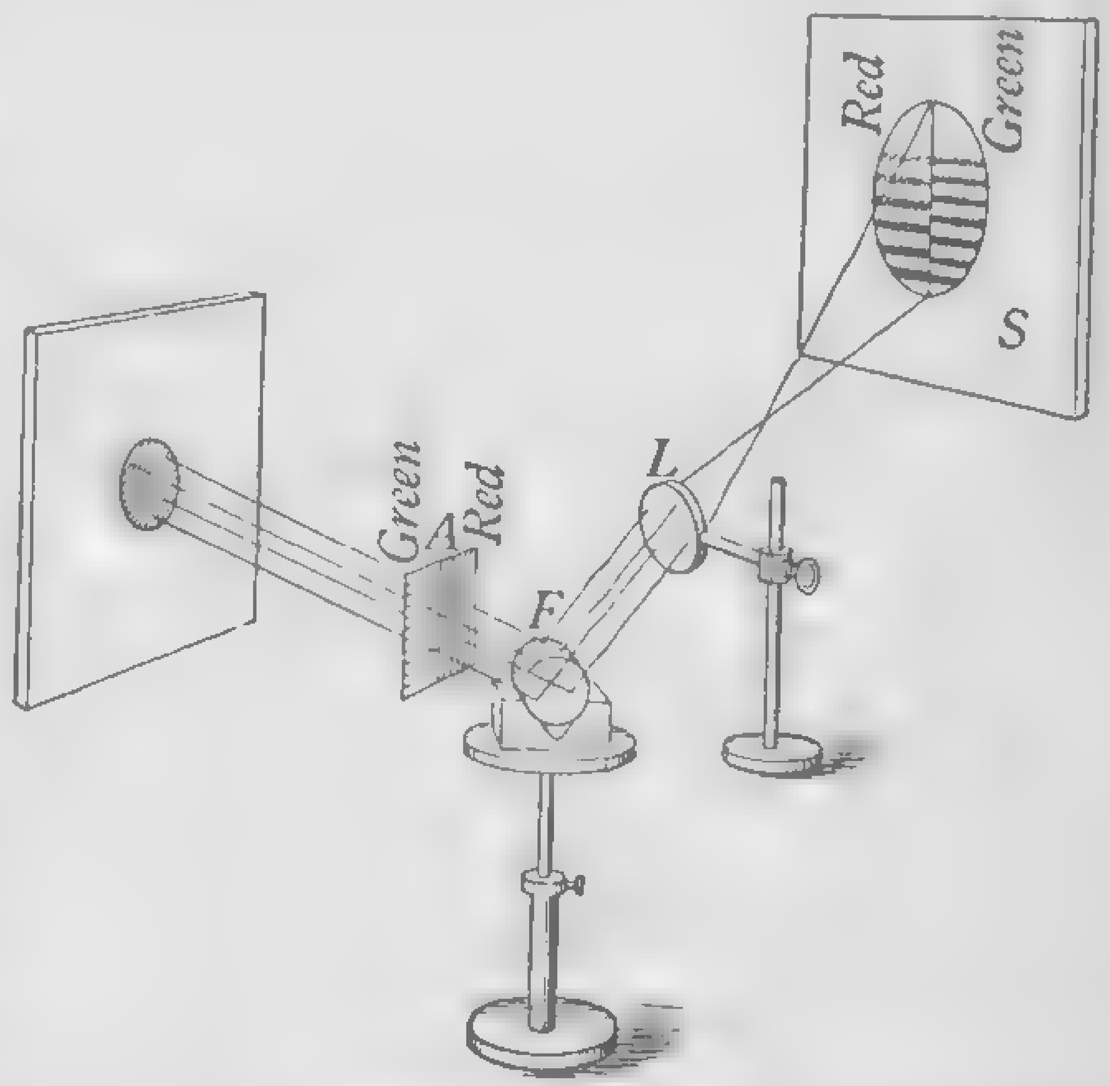


Fig. 448. Projection of soap-film fringes

the side of the film which is covered by the green glass will be seen to cover about the same distance as six fringes on the red side.*

Since it was shown in Fig. 388 that the distance between two dark bands corresponds to an increase of one-half wave length in the thickness of the film, we conclude, from the fact that the dark bands on the red side are farther apart than those on the green side, that red light must have a longer wave length than green light. The wave length, number of waves per centimeter, and rate of vibration of the *central portion* of each colored region of the spectrum are roughly as follows:

Color	Wave Length in Centimeters	Number of Waves per Centimeter	Number of Waves per Second (Frequency)
Violet	.000041	24,400	732,000,000,000,000
Blue	.000047	21,300	639,000,000,000,000
Green	.000052	19,200	576,000,000,000,000
Yellow	.000057	17,500	525,000,000,000,000
Orange	.000062	16,100	483,000,000,000,000
Red	.000071	14,100	423,000,000,000,000

Let the red and green glasses be removed from the path of the beam. The red and green fringes will be seen to be replaced by a series of bands brilliantly colored in different hues. These are due to the fact that the lights of different wave length form interference bands at different places on the screen. Notice that the upper edges of the bands (lower edges in the inverted image) are reddish, whereas the lower edges are bluish. We shall find the explanation of this fact in § 470.

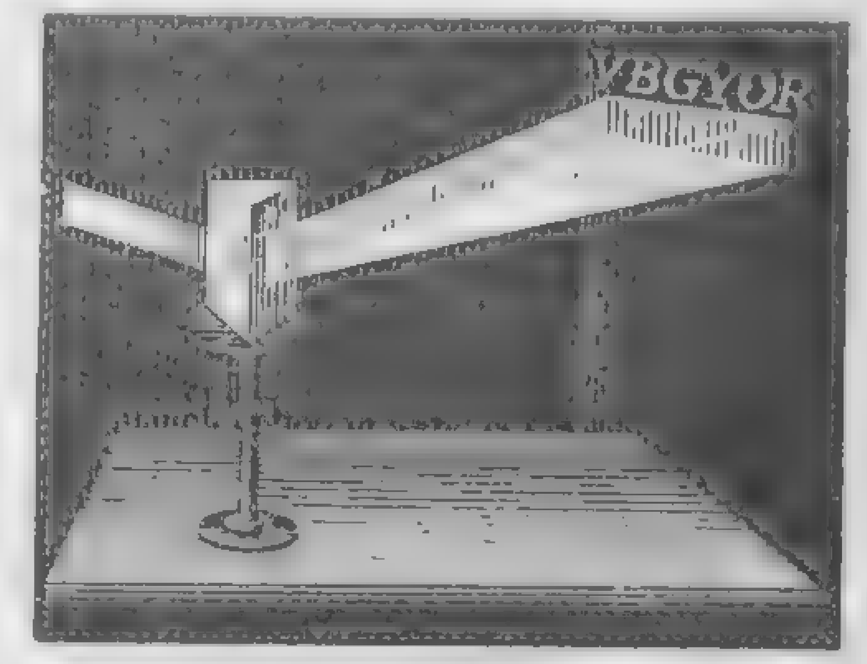


Fig. 449. White light dispersed by a prism

462. Composite nature of white light shown by dispersion. Let a beam of sunlight pass through a narrow slit and fall on a prism, as in Fig. 449. The beam which enters the prism as white light is

* The experiment may be performed at home by simply looking through red and green glasses at a soap film so placed as to reflect white light to the eye.

dispersed into red, yellow, green, blue, and violet lights, although each color merges, by insensible gradations, into the next. This band of color is called a *spectrum*.

We conclude from this experiment that *white light is a mixture of all the colors of the spectrum, from red to violet inclusive.*

463. Color of bodies in white light. Let a piece of red glass be held in the path of the colored beam of light in the experiment of the preceding section. All the spectrum except the red will disappear, thus showing that all the wave lengths except red have been absorbed by the glass. Let a green glass be inserted in the same way. The green portion of the spectrum will remain strong, whereas the other portions will be greatly enfeebled. Hence green glass must have a much less absorbing effect upon wave lengths which correspond to green than upon those which correspond to red and blue. Let the green and red glasses be held one behind the other in the path of the beam. The spectrum will almost completely vanish, for the red glass has absorbed all except the red rays, and the green glass has absorbed these.

We conclude, therefore, that the color which a body has in ordinary daylight is determined by the wave lengths which the body has *not* the power of absorbing. Thus, if a body appears white in daylight, it is because it diffuses or reflects all wave lengths equally to the eye, and does not absorb one set more than another. For this reason the light which comes from it to the eye is of the same composition as daylight or sunlight. If, however, a body appears red in daylight, it is because it absorbs the red rays of the white light which falls upon it less than it absorbs the others, so that the light which is diffusely reflected contains a larger proportion of red wave lengths than is contained in ordinary light. Similarly, a body appears yellow, green, or blue when it absorbs less of one of these colors than of the rest of the colors contained in white light, and therefore sends a preponderance of some particular wave length to the eye.

464. Color of bodies placed in colored lights. If a body which appears white in sunlight be placed in the red part of the spectrum, it will appear to be red; in the blue part of the spectrum it will

appear to be blue; etc. This confirms the conclusion of the last paragraph, that a white body has the power of diffusely reflecting all the colors of the spectrum equally.

Next let a skein of red yarn be held in the blue end of the spectrum. It will appear nearly black. In the red end of the spectrum it will appear strongly red. Similarly, a skein of blue yarn will appear nearly black in all the colors of the spectrum except blue, where it will have its proper color.

These effects are evidently due to the fact that the red yarn, for example, has the power of diffusely reflecting red wave lengths copiously, but of absorbing, to a large extent, the others. Hence, when held in the blue end of the spectrum, it sends but little color to the eye, since no red light is falling upon it.

Soak a handful of asbestos or cotton batting in a saturated salt solution; squeeze out most of the brine; pour over the material a quantity of strong alcohol. A minute or so after being ignited, this will produce a large flame of almost pure-yellow light. In a darkened room allow the yellow light to fall strongly upon a spectrum chart of six colors. The only color on the chart that appears natural is the yellow.

The blue-green glass globe of the so-called *daylight* electric lamp absorbs the excess red and yellow light of the filament; hence, although the total amount of light received from the filament is reduced, the various colors which pass through are mixed in about the same proportions as we find them in daylight. Objects examined under this lamp, therefore, appear the same in color as when seen in daylight.

465. Compound colors. It must not be inferred from the preceding paragraphs that every color except white has one definite wave length, for the same effect may be produced on the eye by a mixture of several different wave lengths as is produced by a single wave length. This statement may be proved by the use of an apparatus known as Newton's color disk (Fig. 450). The arrangement makes it possible to rotate differently colored sectors so rapidly before the eye that the

effect is precisely the same as though the colors came to the eye simultaneously. If one half of the disk is red and the other half green, the rotating disk will appear yellow, the color being very similar to the yellow of the spectrum. If green and violet are mixed in the same way, the result will be light blue. Although the colors produced in this way are not distinguishable by the eye from spectral colors, it is obvious that their physical constitution is wholly different; for whereas a spectral color consists of waves of a single wave length, the colors produced by mixture are compounds of several wave lengths. For this reason the spectral colors are called pure and the others compound. In order to tell whether the color of an object is pure or compound, it is only necessary to observe it through a prism. If it is compound, the colors will be separated, giving an image of the object for each color. If it is pure, the object will appear through the prism exactly as it does without the prism.

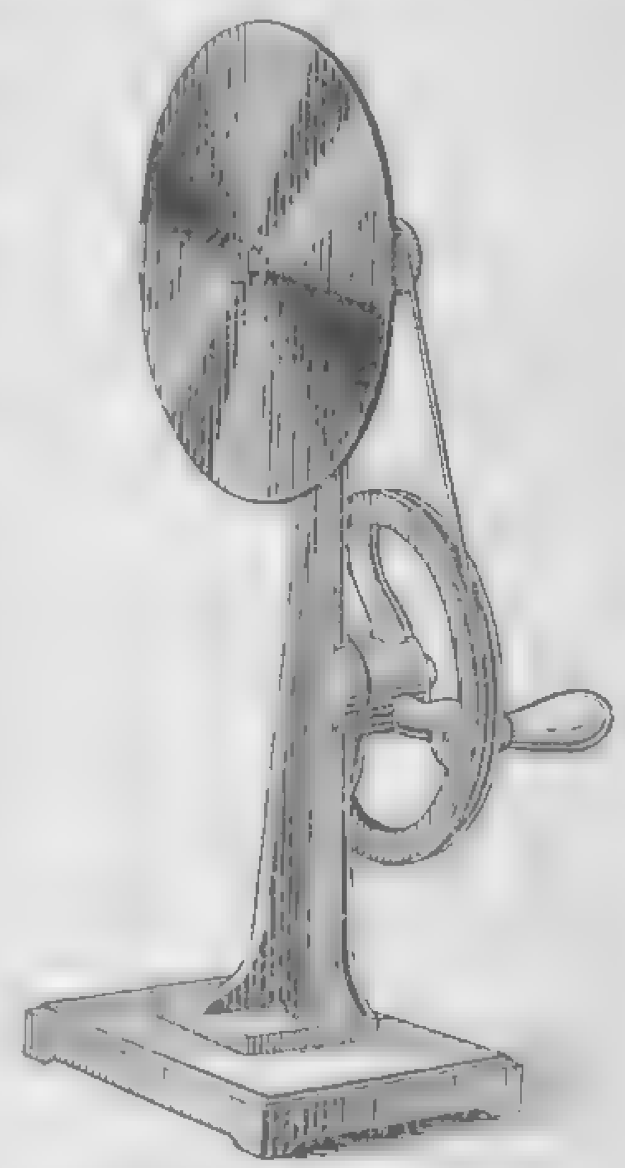


FIG. 450. Newton's color disk

By compounding colors in the way described above we can produce many which are not found in the spectrum. Thus, mixtures of red and blue give purple or crimson; mixtures of black with red, orange, or yellow give rise to the various shades of brown. Lavender may be formed by adding seven parts of white to eight of blue and one of red; lilac, by adding two parts of white to one part of red and three parts of blue; olive, by adding one part of black to two parts of green and one of red.

466. Complementary colors. Since white light is a combination of all the colors from red to violet inclusive, it might be expected that if one or several of these colors were subtracted from white light, the residue would be colored light.

To test this experimentally let a beam of sunlight be passed through a slit s, a prism P, and a lens L, to a screen S, arranged as in Fig. 451. A spectrum will be formed at RV, the position conjugate to the slit s, and a pure white spot will appear on the screen when it is at the position which is conjugate to the prism face ab. Let a card be slipped into the path of the beam at R, so as to cut off the red portion of the light. The spot on S will appear a brilliant shade of greenish blue. This is the compound color left after red is taken from the white light. This shade of blue is therefore called the *complementary color* of the red which has been subtracted. Two *complementary colors* are therefore defined as any two colors which produce white when added to each other.

Let the card be slipped in from the side of the blue rays at V. The spot will first take on a yellowish tint when the violet alone is cut out; and as the card is slipped farther in, the image will become a deep shade of red when violet, blue, and part of the green are cut out.

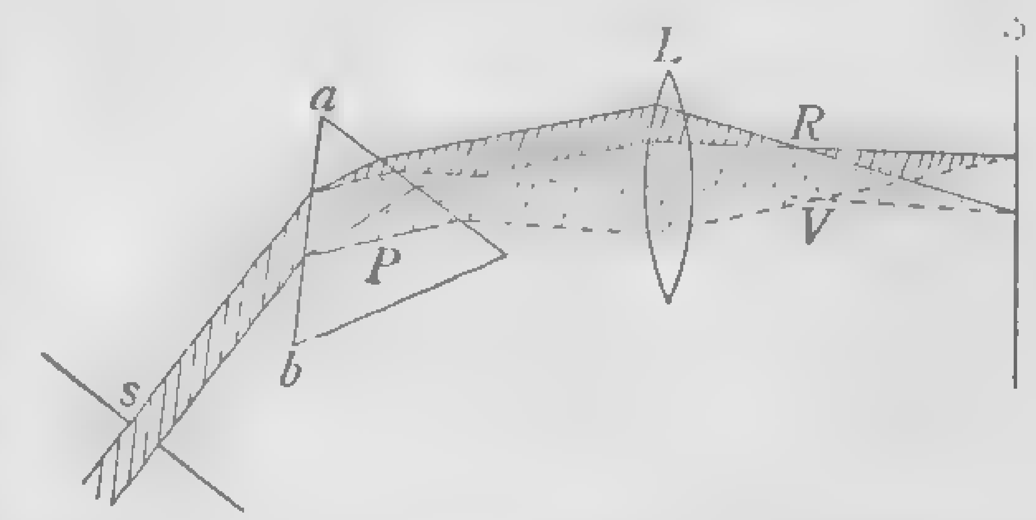


FIG. 451. Recombination of spectral colors into white light

Next let a lead pencil be held vertically between R and V so as to cut off the middle part of the spectrum; that is, the yellow and green rays. The remaining red, blue, and violet will unite to form a brilliant purple. In each case the color on the screen is the complement of that which is cut out.

467. Retinal fatigue. Let the gaze be fixed intently for not less than twenty or thirty seconds on a point at the center of a block of any brilliant color — for example, red. Then look off at a dot on a white wall or a piece of white paper, and hold the gaze fixed there for a few seconds. The brilliantly colored block will appear on the white wall, but its color will be the *complement* of that first looked at.

The explanation of this phenomenon, which comes from so-called *retinal fatigue*, is found in the fact that although the white surface is sending waves of all colors to the eye, the nerves which responded to the color first looked at have become fatigued, and hence fail to respond to this color when

it comes from the white surface. Therefore the sensation produced is that caused by white light minus this color; that is, to the complement of the original color. A study of the spectral colors by this method shows that the following colors are complementary:

Red	Orange	Yellow	Violet	Green
Bluish green	Greenish blue	Blue	Greenish yellow	Crimson

468. Color of pigments. When yellow light is added to the proper shade of blue, white light is produced, since these colors are complementary. But if a yellow pigment is added to a blue one, the color of the mixture will be green. This is because the yellow pigment removes the blue and violet by absorption, and the blue pigment removes the red and yellow, so that only green is left.

When pigments are mixed, therefore, each one *subtracts* certain colors from white light, and the color of the mixture is that color which escapes absorption by the different ingredients. Adding *pigments* and adding *colors*, as in § 465, are therefore wholly dissimilar processes and produce widely different results.

469. Three-color printing. It is found that all colors can be produced by suitably mixing with the color disk (Fig. 450) three spectral colors, namely red, green, and blue-violet. These are therefore called the *three primary colors.* The so-called primary pigments are simply the complements of these three primary colors. They are, in order, peacock blue, crimson, and light yellow. The three primary colors when mixed yield white. The three primary pigments when mixed yield black, because together they subtract all the ingredients from white light. The process of three-color printing consists in mixing on a white background, that is, on white paper, the three primary *pigments* in the following way: Three different photographs of a given-colored object are taken, each through a *filter* of gelatin stained the color of one of the primary colors. From these photographs halftone *blocks* are

THREE-COLOR PRINTING

1, yellow impression (negative made through a blue-violet filter); 2, crimson impression (negative made through a green filter); 3, crimson on yellow; 4, blue impression (negative made through a red filter); 5, yellow, crimson, and blue combined (the final product). The circles at the right show the colors of ink used in making each impression. Notice the different colors in 5, which are made by combining yellow, crimson, and blue

made in the usual way. The colored picture is then made by carefully superposing prints from these blocks, using with each an ink whose color is the complement of that of the filter through which the original negative was taken. The plate opposite page 440 illustrates fully the process. It will be interesting to examine differently colored portions with a lens of moderate magnifying power.

470. Colors of thin films. The study of complementary colors has furnished us with the key to the explanation of the fact, observed in § 461, that the upper edge of each colored band produced by the water wedge is reddish, whereas the lower edge is bluish. On the upper edge the shorter blue waves are destroyed by interference and a complementary red color is left; but on the lower edge of each fringe, where the film is thicker, the longer red waves interfere, leaving a complementary blue. In fact, each wave length of the incident light produces a set of fringes, and it is the superposition of these different sets which gives the resultant colored fringes. Where the film is too thick the overlapping is so complete that the eye is unable to detect any trace of color in the reflected light.

In films which are of uniform thickness, instead of wedge-shaped, the color is also uniform, so long as the observer does not change the angle at which the film is viewed. With any change in this angle the thickness of film through which the light must pass in coming to the observer changes also, and hence the color changes. This explains the beautiful play of iridescent colors seen in soap bubbles, thin oil films, mother of pearl, etc.

471. Chromatic aberration. It has heretofore been assumed that all the waves which fall on a lens from a given source are brought to one and the same focus. But since blue rays are bent more than red ones in passing through a prism, it is clear that in passing through a lens the blue light must be brought to a focus at some point v (Fig. 452) nearer the lens than r, where the red light is focused, and that the foci for intermediate colors must fall in intermediate positions.

It is for this reason that an image formed by a simple lens is always fringed with color.

Let a card be held at the focus of a lens placed in a beam of sunlight (Fig. 452). If the card is slightly nearer the lens than the focus, the spot of light will be surrounded by a red fringe, for the red rays, being least refracted, are on the outside. If the card is moved out beyond the focus, the red fringe will be found to be replaced by a blue one; for after crossing at the focus it will be the more refrangible rays which will then be found outside.

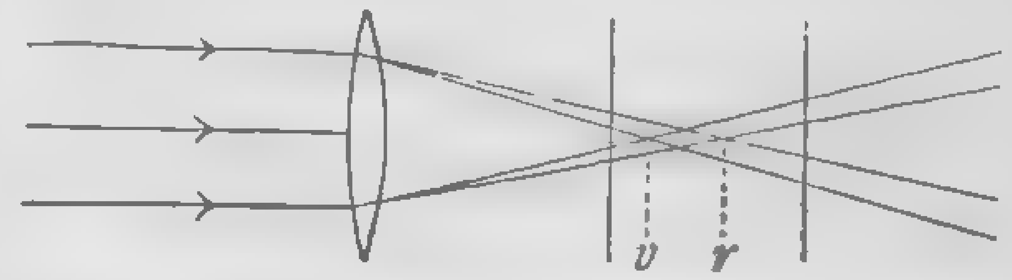


FIG. 452. Chromatic aberration of lens

This dispersion of light produced by a lens is called *chromatic aberration.*

472. Achromatic lenses. The color effect caused by the chromatic aberration of a simple lens greatly impairs its usefulness. Fortunately, however, it has been found possible to eliminate this effect almost completely by combining into one lens a convex lens of crown glass and a concave lens of flint glass (Fig. 453). The first lens produces both bending and dispersion, whereas the second almost completely overcomes the dispersion without entirely overcoming the bending. Such lenses are called *achromatic lenses.* The first one was made by John Dollond in London in 1758. They are used in the construction of all good telescopes and microscopes.

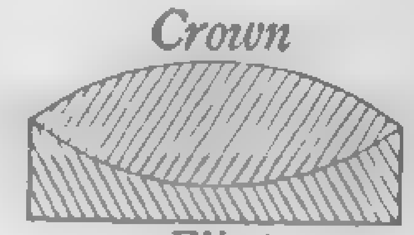


FIG. 453. An achromatic lens

SUMMARY. Pitch in sound and color in light depend upon wave frequency.

Dispersion is due to unequal refraction of waves of different length when they pass obliquely into or out of a medium.

The color of a body in white light is determined by the wave length it cannot absorb.

The unnatural appearance of a body in colored light is due to its not receiving all the colors which it is capable of reflecting.

QUESTIONS AND PROBLEMS

1. What is the physical difference between red light and blue light?

2. Draw a figure to show how a spectrum is formed by a prism, and indicate the relative positions of the red, the yellow, the green, and the blue in this spectrum.

3. Does blue light travel more slowly or faster in glass than red light? How do you know?

4. What determines the color of an opaque body? a transparent body?

5. What is "white"? What is "black"? Why is coal black?

6. Explain why a block of ice is transparent whereas snow is opaque and white.

7. What is the appearance of a bunch of green grass when seen by pure red light? Explain.

8. What will be the apparent color of a red body when it is in a room to which only green light is admitted? Why?

9. Why does any object seen through a piece of red glass appear to be either red or black?

10. Why do white bodies look blue when seen through a blue glass?

11. What color would a yellow object appear to have if looked at through a blue glass? (Assume that the yellow is a pure color.)

12. A gas flame is distinctly yellow as compared with sunlight. What wave lengths, then, must be comparatively weak in the spectrum of a gas flame?

13. Why does dark blue appear black by candle light?

14. Certain blues and greens cannot be distinguished from each other by candle light. Explain.

SPECTRA

473. The rainbow. There is formed in nature a very beautiful spectrum with which everyone is familiar, the *rainbow.*

Let a spherical bulb F (Fig. 454) $1\frac{1}{2}$ or 2 inches in diameter be filled with water and held in the path of a beam of sunlight which enters the room through a hole in a piece of cardboard AB. A

miniature rainbow will be formed on the screen around the opening, the violet edge of the bow being toward the center of the circle and the red outside. A beam of light which enters the flask at C is there both refracted and dispersed; at D it is totally reflected; and at E it is again refracted and dispersed on passing out into the air. Since in both the refractions the violet is bent more than the red, it is obvious that it must return nearer to the direction of the incident beam than the red rays. If the flask were a perfect sphere, the angle included between the incident ray OC and the emergent red ray ER would be 42°; and the angle between the incident ray and the emergent violet ray EV would be 40°.

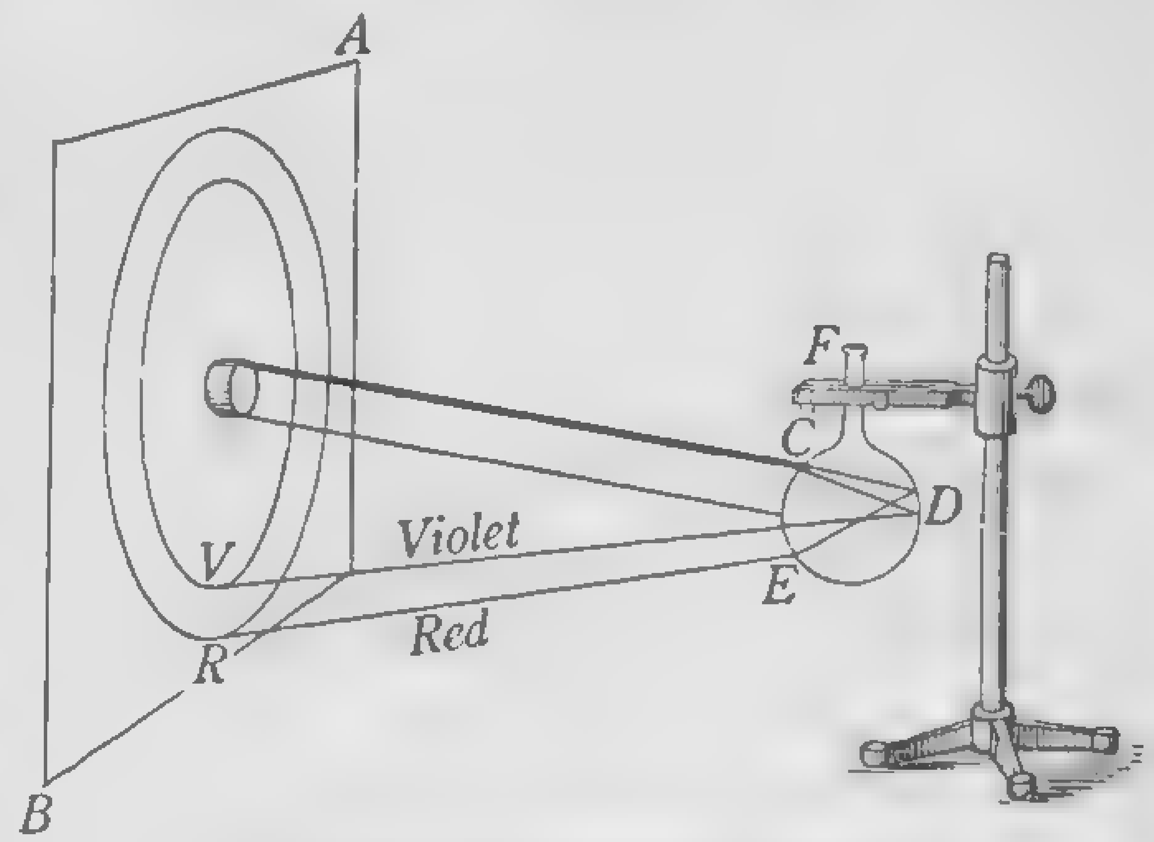


FIG. 454. Artificial rainbow

The actual rainbow seen in the heavens is caused by the refraction and reflection of light in the drops of water in the air, which act exactly as did the flask in the preceding experiment. If the observer is standing at E with his back to the sun, the light which comes from the drops so as to make an angle of 42° (Fig. 455) with the line drawn from the observer to the sun must be red light; and the light which comes from drops which are at an angle of 40° from the eye must be violet light. In direct sunshine the prismatic color seen in a dewdrop changes to another color when the head is shifted sidewise.

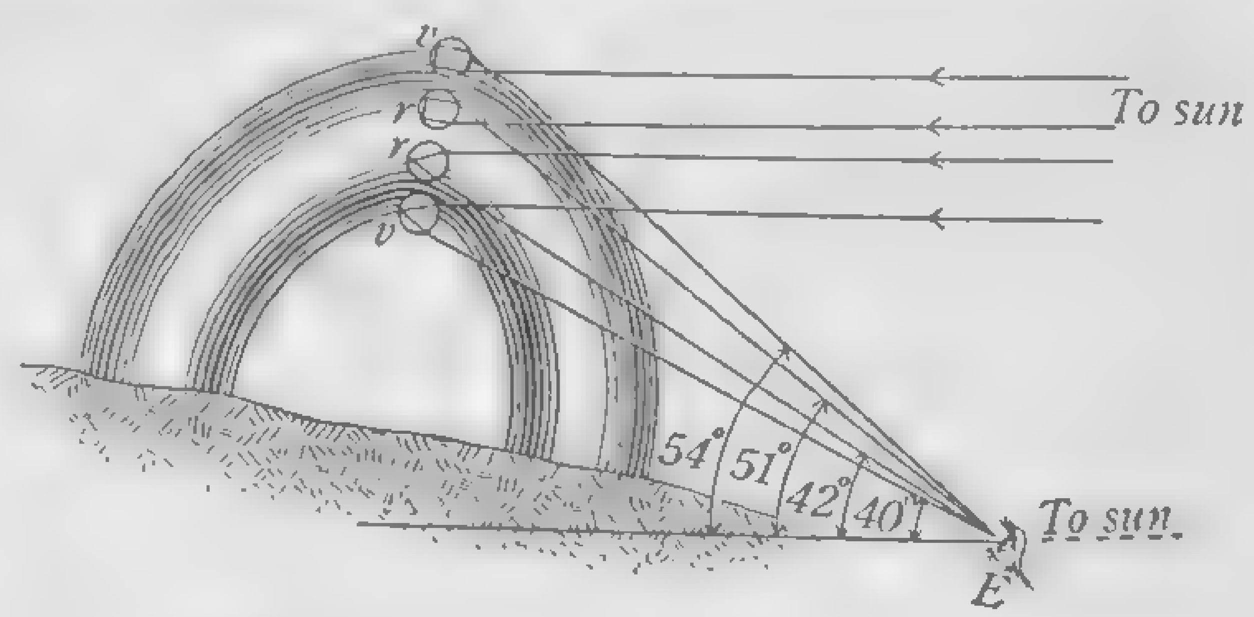


FIG. 455. Primary and secondary rainbows

It is clear that those drops whose direction from the eye makes any particular angle with the line drawn from the eye to the sun must lie on a circle whose center is on that line. Hence we see a circular arc of light which is violet on the inner edge and red on the outer edge. A second bow having the red on the inside and the violet on the outside is often seen outside the one just described, and concentric with it. This bow arises from rays which have undergone two internal reflections and two refractions, in the manner shown in Fig. 455.

474. Continuous spectra. Let a Bunsen burner arranged to produce a white flame be placed behind a slit s (Fig. 456). Let the slit be viewed through a prism P. The spectrum will be a continuous band of color. If the air is admitted at the base of the burner and a clean platinum wire held in the flame directly in front of the slit, the white-hot platinum will also give a continuous spectrum.*

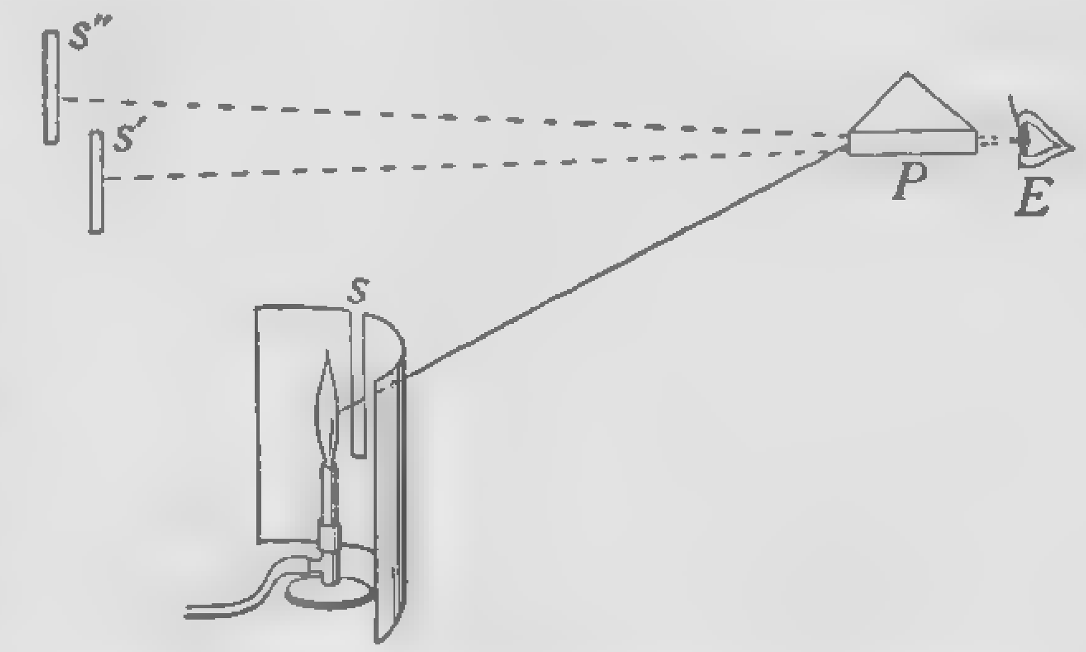


FIG. 456. Arrangement for viewing spectra

All incandescent solids and liquids are found to give spectra of this type which contain all the wave lengths from the extreme red to the extreme violet. The continuous spectrum of a luminous gas flame comes from the incandescence of solid particles of carbon suspended in the flame. The presence of these solid particles is proved by the fact that soot is deposited on bodies held in a white flame.

475. Bright-line spectra. Let a bit of asbestos or a platinum wire be dipped into a solution of common salt (sodium chloride) and held in the flame, care being taken that the wire itself is held so

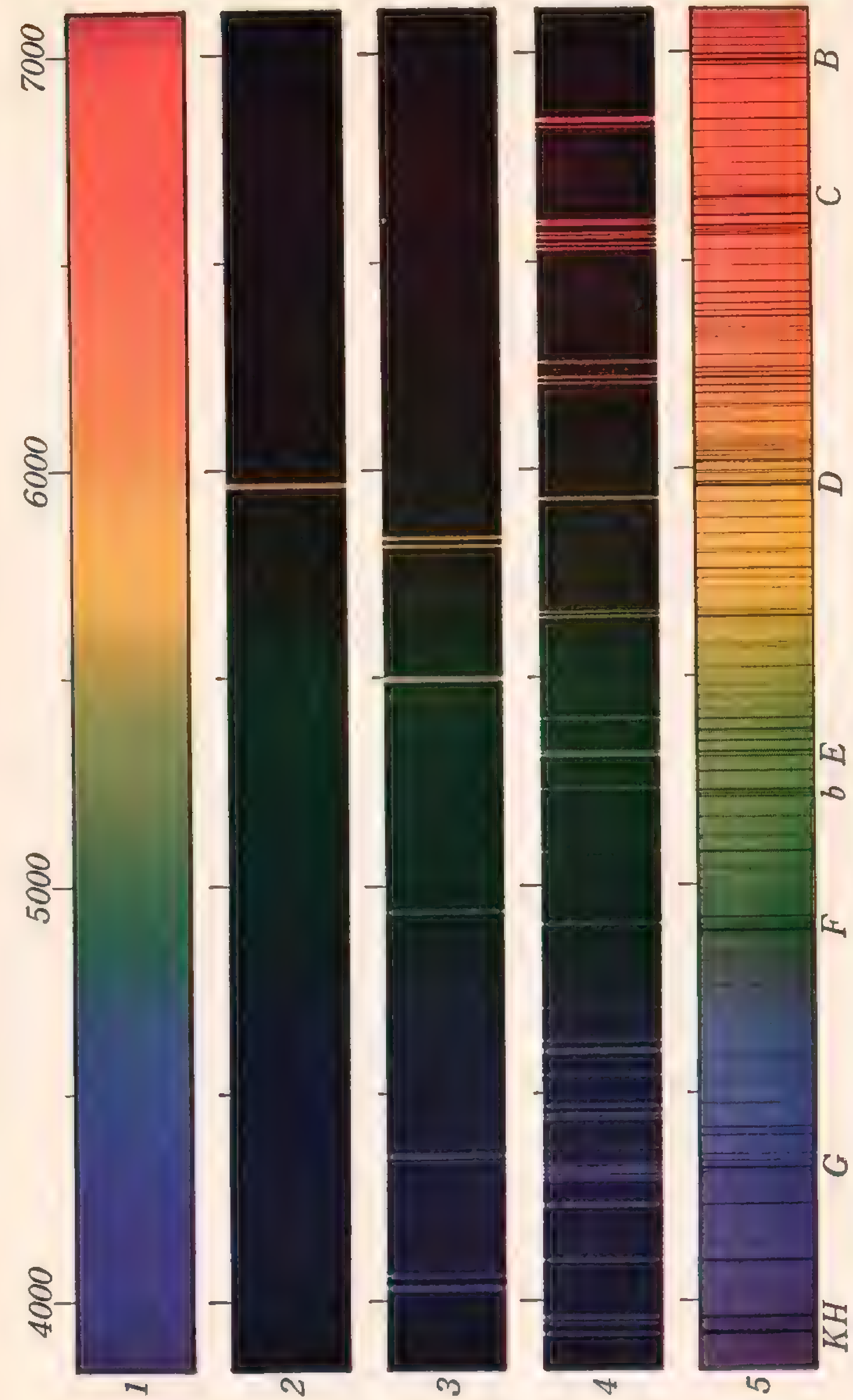
* By far the most satisfactory way of performing these experiments with spectra is to provide the class with cheap plate-glass prisms, like those used in Experiment 63 of "Exercises in Laboratory Physics" by Millikan, Gale, and Davis, rather than to attempt to project line spectra.

low that the spectrum due to it cannot be seen. The continuous spectrum of the preceding paragraph will be replaced by a clearly defined yellow image of the slit, which occupies the position of the yellow portion of the spectrum. This shows that the light from the sodium flame is not a compound of a number of wave lengths, but is rather of just the wave length which corresponds to this particular shade of yellow. The light is now coming from the incandescent sodium vapor and not from an incandescent solid, as in the preceding experiments.

Let another platinum wire be dipped in a solution of lithium chloride and held in the flame. Two distinct images of the slit, s' and s'' (Fig. 456), will be seen, one in red and one in yellow. Let calcium chloride be introduced into the flame. One distinct image of the slit will be seen in the green and another in the red. Strontium chloride will give a blue and a red image, etc. (The yellow sodium image will probably be present in each case, because sodium is present as an impurity in nearly all salts.)

These narrow images of the slit in the different colors are called the characteristic *spectral lines* of the substances. The experiments show that incandescent vapors and gases give rise to *bright-line spectra,* and not continuous spectra like those produced by incandescent solids and liquids (see on opposite page). The method of analyzing compound substances through a study of the lines in the spectra of their vapors is called *spectrum analysis*. It was first used by Bunsen in 1859.

476. The solar spectrum. Let a beam of sunlight pass first through a narrow slit S (Fig. 457) not more than $\frac{1}{5}$ millimeter in width, then through a prism P, and finally let it fall on a screen S', as shown in Fig. 457. Let the position of the prism be changed until a beam of white light is reflected from one of its faces to that portion of the screen which was previously occupied by the central portion of the spectrum. Then let a lens L be placed between the prism and the slit, and moved back and forth until a perfectly sharp white image of the slit is formed on the screen. This adjustment is made in order to get the slit S and the screen S' in the positions of conjugate foci of the lens. Now let the prism be turned to its original position. The spectrum on the screen will



DIFFERENT TYPES OF SPECTRA

1, continuous spectrum from an incandescent solid; 2, bright line spectrum of sodium; 3, bright line spectrum of mercury; 4, bright line spectrum of calcium; 5, absorption spectrum of the sun showing some of the strongest Fraunhofer lines

then consist of a series of colored images of the slit arranged side by side. This is called a pure spectrum, to distinguish it from the spectrum shown in Fig. 449, in which no lens was used to bring the rays of each particular color to a particular point, and in which there was therefore much overlapping of the different colors. If the slit and screen are exactly at conjugate foci of the lens, and if the slit is sufficiently narrow, the spectrum will be seen to be crossed vertically by certain dark lines.

These lines were first observed by the Englishman Wollaston in 1802, and were first studied carefully by the German Fraunhofer in 1814, who counted and mapped out as many as seven hundred of them. They are called, after him, the *Fraunhofer lines*. Their existence in the solar spectrum shows that certain wave lengths are absent from sunlight, or, if not entirely absent, are at least much weaker than their neighbors. When the experiment is performed as described above, it will usually not be possible to count more than five or six distinct lines. Kirchhoff explained these lines.

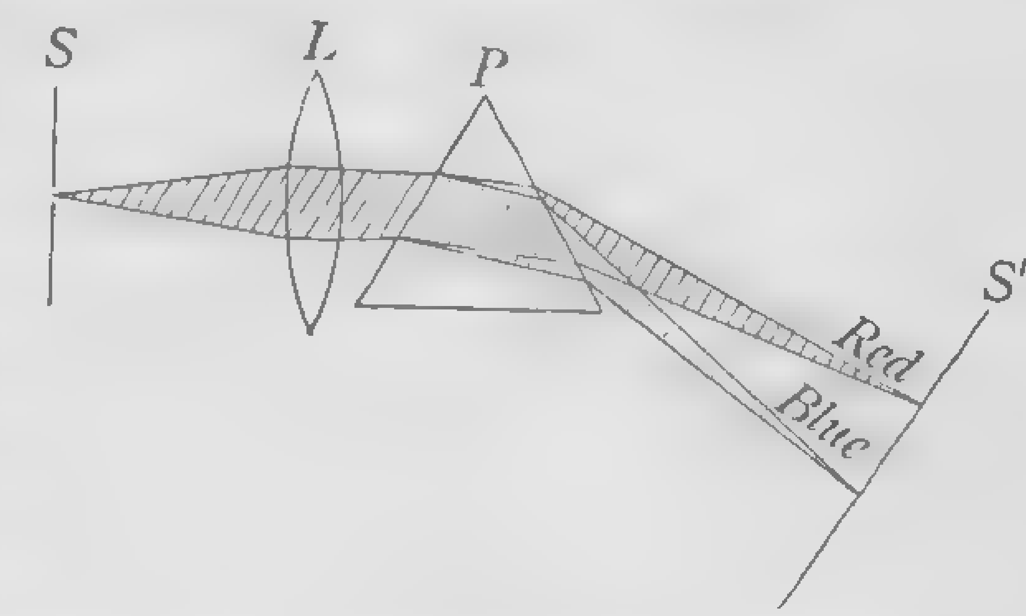


FIG. 457. Arrangement for obtaining a pure spectrum

477. Explanation of the Fraunhofer lines. Let the solar spectrum be projected as in § 476. Let a few small bits of metallic sodium be laid upon a loose wad of asbestos which has been saturated with alcohol. Let the asbestos so prepared be held to the left of the slit, or between the slit and the lens, and there ignited. A black band will at once appear in the yellow portion of the spectrum, in the place where the color is exactly that of the sodium flame itself; or, if the focus was sufficiently sharp to permit a dark line to be seen in the yellow before the sodium was introduced, this line will grow very much blacker when the sodium is burned. Evidently, then, this dark line in the yellow part of the solar spectrum is in some way due to sodium vapor through which the sunlight has somewhere passed.

The experiment at once suggests the explanation of the Fraunhofer lines. The white light which is emitted by the hot nucleus of the sun, and which contained all wave lengths, has had certain wave lengths weakened by absorption as it passed through the vapors and gases surrounding the sun and the earth. For it is found that *every gas or vapor will absorb exactly those wave lengths which it is itself capable of emitting when incandescent.* This is for precisely the same reason that a tuning fork will respond to, that is, absorb, only vibrations which have the same period as those which it is itself able to emit. Since, then, the dark line in the yellow portion of the sun's spectrum is in exactly the same place as the bright yellow line produced by incandescent sodium vapor, or the dark line which is produced whenever white light shines through sodium vapor, we infer that sodium vapor must be contained in the sun's atmosphere. By comparing in this way the positions of the lines in the spectra of different elements with the positions of various dark lines in the sun's spectrum, many of the elements which exist on the earth have been proved to exist also in the sun. For example, Kirchhoff showed that the four hundred and sixty bright lines of iron which were known to him were all exactly matched by dark lines in the solar spectrum. Fig. 458 shows a copy of a photograph of a portion of the solar spectrum in the middle, and the corresponding bright-line spectrum of iron each side of it. (This was taken from a portion of the blue

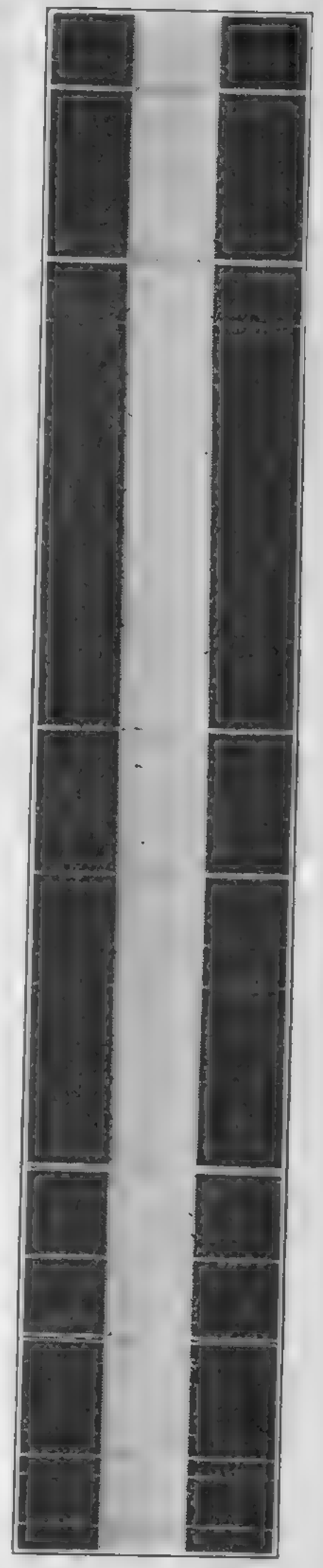


FIG. 458. Comparison of solar and iron spectra

only of the spectrum.) It will be seen that each bright line of iron coincides exactly with a dark line of the solar spectrum.

478. Doppler's principle applied to light waves. We have noted (see "The Doppler effect," § 388, p. 353) that the effect of the motion of a sounding body toward an observer is to shorten slightly the wave length of the note emitted, and the effect of motion away from an observer is to increase the wave length. Similarly, when a star is moving toward the earth, each particular wave length emitted will be slightly less than the wave length of the corresponding light from a source on the earth's surface. Hence in this star's spectrum all the lines will be displaced slightly toward the violet end of the spectrum. If a star is moving away from the earth, all its lines will be displaced toward the red end. From the direction and amount of displacement, therefore, we can calculate the velocity with which a star is moving toward the solar system or receding from it. Observations of this sort have shown that some stars are moving through space toward the solar system with a velocity of 150 miles per second, while others are moving away from it with almost equal velocity. The whole solar system appears to be sweeping through space with a velocity of about 12 miles per second; but even at this rate it would be at least 70,000 years before the earth would come into the neighborhood of the nearest star, even if it were moving directly toward it.

SUMMARY. Continuous spectra are produced by light from incandescent solids and liquids.

Bright-line spectra come from incandescent vapors or gases.

Absorption spectra are produced by light passing from an incandescent solid or liquid through an incandescent vapor or gas.

QUESTIONS AND PROBLEMS *

1. In what part of the sky will a rainbow appear if it is formed in the early morning?

2. Why is a rainbow never seen during the middle part of the day?

3. Explain the cause of the formation of a continuous spectrum when light from an incandescent lamp is passed through a prism.

* Supplementary questions and problems for Chapter XX are given in the Appendix.

4. How does a continuous spectrum differ from that obtained when the source of light is a Bunsen burner in which sodium is being vaporized?

5. Why do we believe that there is sodium in the sun?

6. What sort of spectrum should moonlight give? (The moon has no atmosphere.)

7. If you were given a mixture of a number of salts, how would you proceed, with a Bunsen burner, a prism, and a slit, to determine whether or not there was any calcium in the mixture?

8. Draw a diagram of a slit, a prism, and a lens, so placed as to form a pure spectrum.

CHAPTER XXI

INVISIBLE RADIATIONS

Radiation from a Hot Body

479. Invisible portions of the spectrum. When a spectrum is photographed, the effect on the photographic plate is found to extend far beyond the limits of the shortest visible violet rays. These so-called *ultra-violet rays* have been photographed down to a wave length of .00000136 centimeter, which is only one thirtieth the wave length of the shortest violet waves.

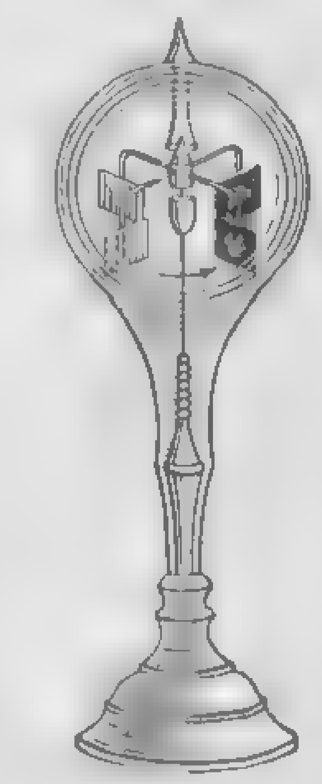


Fig. 459. The Crookes radiometer

The longest rays visible in the extreme red have a wave length of about .00008 centimeter, but delicate thermoscopes reveal a so-called *infra-red* portion of the spectrum, the investigation of which was carried, in 1912, by Rubens and Von Baeyer of Berlin, to wave lengths as long as .03 centimeter, 400 times as long as the longest visible rays.

The presence of these long heat rays may be detected by means of the radiometer (Fig. 459), an instrument perfected by E. F. Nichols at Dartmouth. In its common form it consists of a partially exhausted bulb, within which is a little aluminum wheel carrying four vanes blackened on one face and polished on the other. When the instrument is held in sunlight or before a lamp, the vanes rotate in such a way that the blackened faces always move away from the source of radiation, because they absorb ether waves better than do the polished faces, and thus become hotter. The heated air in contact with these faces then exerts a greater pressure against them than does the air in contact with the polished faces.

Let the radiometer be placed just beyond the red end of the spectrum. It will indicate the presence here of heat rays of even greater energy than those in the visible spectrum. Further, let a red-hot iron ball and one of the detectors be placed at conjugate foci of a large mirror (Fig. 460). The invisible heat rays will be found to be reflected and focused just as are light rays. Next let a flat bottle filled with water be inserted between the detector and any source of heat. It will be found that water, although transparent to light rays, absorbs nearly all the infra-red rays. But if the water is replaced by carbon bisulphide, the infra-red rays will be freely transmitted, even though the liquid is rendered opaque to light waves by dissolving iodine in it.

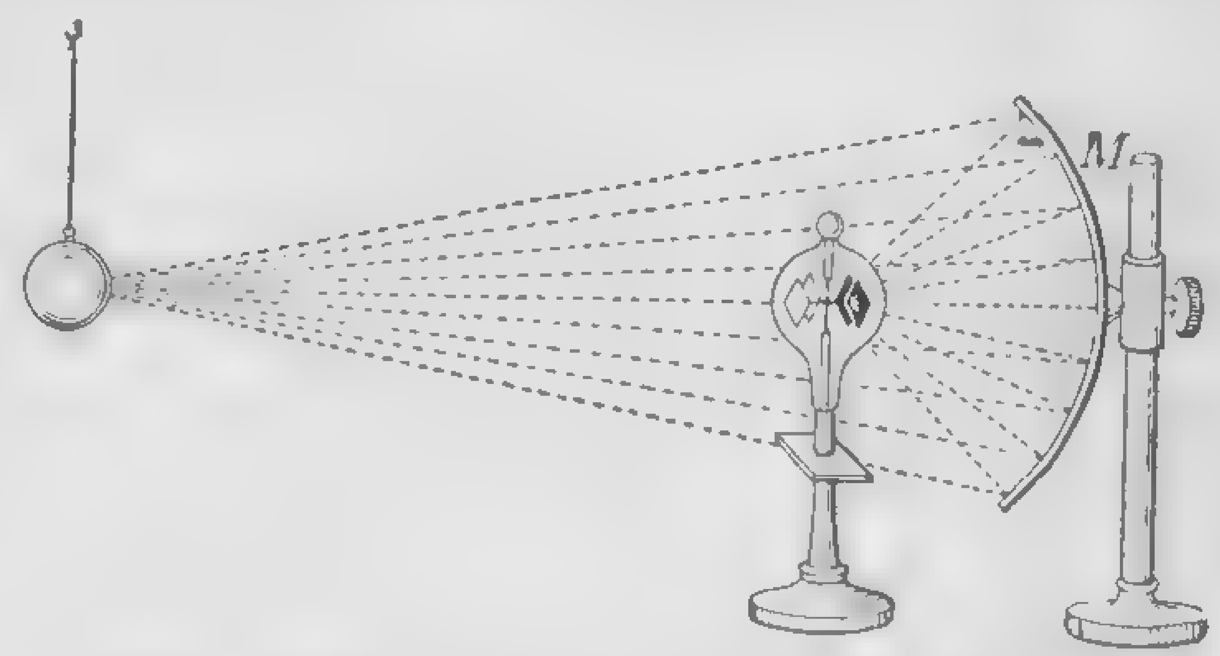


FIG. 460. Reflection of infra-red rays

480. Radiation and temperature. All bodies, even such as are at ordinary temperatures, are continually radiating energy in the form of ether waves. This is proved by the fact that even if a body is placed in the best vacuum obtainable, it continually falls in temperature when surrounded by a colder body, for example, liquid air. The ether waves emitted at ordinary temperatures are doubtless very long as compared with light waves. As the temperature is raised, more and more of these long waves are emitted, but shorter and shorter waves are continually added. At about 525° C. the first visible waves, that is, those of a dull red color, begin to appear. From this temperature on, because of the addition of shorter and shorter waves, the color changes continuously, — first to orange, then to yellow, and, finally, between 800° C. and 1200° C., to white. In other words, all bodies get "red-hot" at about 525° C. and "white-hot" at from 800° C. to 1200° C.

Some idea of how rapidly the total radiation of ether waves increases with increase of temperature may be obtained from

the fact that a hot platinum wire gives out thirty-six times as much light at 1400° C. as it does at 1000° C., although at the latter temperature it is already white-hot. The radiations from a hot body are sometimes classified as heat rays, light rays, and chemical, or actinic, rays. The classification is, however, misleading, since all ether waves are heat waves in the sense that, when absorbed by matter, they produce heating effects, that is, molecular motions. *Radiant heat is, then, the radiated energy of ether waves of any and all wave lengths.*

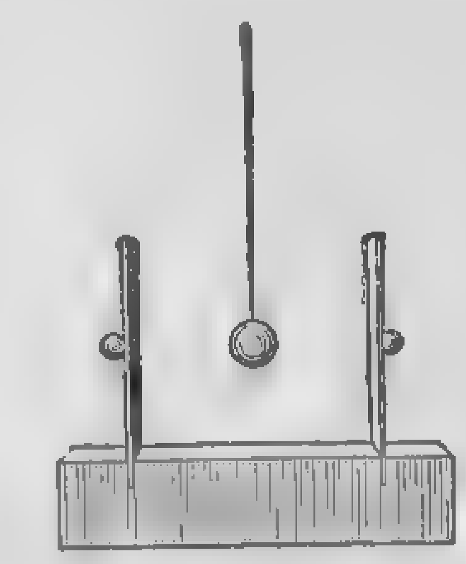


FIG. 461. Good reflectors are poor absorbers

481. Radiation and absorption. Although all substances begin to emit waves of a given wave length at approximately the same temperature, the total rate of emission of energy at a given temperature varies greatly with the nature of the radiating surface. In general, experiment shows that *surfaces which are good absorbers of ether radiations are also good radiators.* From this it follows that *surfaces which are good reflectors,* like the polished metals, *must be poor radiators.*

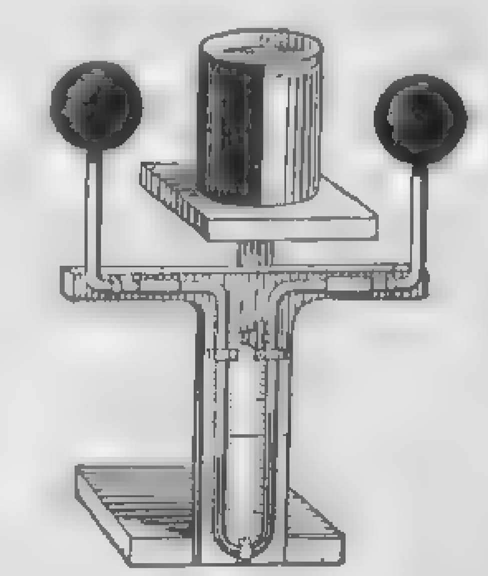


FIG. 462. Good absorbers are good radiators

Thus, let two sheets of tin, 5 or 10 centimeters square, one brightly polished and the other covered on one side with lampblack, be placed in vertical planes about 10 centimeters apart, the lampblacked side of one facing the polished side of the other. Let a small ball be stuck with a bit of wax to the outer face of each. Then let a hot metal plate or ball (Fig. 461) be held midway between the two. The wax on the tin with the blackened face will melt and its ball will fall first, showing that the lampblack absorbs the heat rays faster than does the polished tin. Now let two blackened glass bulbs be connected, as in Fig. 462, through a U-tube containing colored water, and let a well-polished tin can, one side of which has been blackened, be filled with boiling water and placed between them. The motion

of the water in the U-tube will show that the blackened side of the can is radiating heat much more rapidly than the other, although the two are at the same temperature.

Make a black spot on a sheet of white paper with graphite, lampblack, or charcoal, and then with a lens held in sunshine find what time is required to set fire to the paper when the light is concentrated on the black spot. Note the time required when the light is concentrated on the white part of the paper.

SUMMARY. Light waves comprise less than an octave of frequencies, an exceedingly small fraction of the total range of ether waves.

Increase in temperature adds continually shorter and shorter waves and increases the intensity of all wave lengths.

Good absorbers are good radiators and poor absorbers are poor radiators.

QUESTIONS AND PROBLEMS

1. How are ultra-violet waves detected? What apparatus is used to reveal infra-red waves?

2. Which emits the more red rays, a white-hot iron or the same iron when it is red-hot?

3. Explain how the heat of the sun warms the earth.

4. Sunlight in coming to the eye travels a much longer air path at sunrise and sunset than it does at noon. Since the sun appears red or yellow at these times, what rays are absorbed most by the atmosphere?

5. When one is sitting in front of an open-grate fire, does he receive most heat by conduction, by convection, or by radiation?

6. Glass transmits all the visible waves, but does not transmit the long infra-red rays. From this fact explain the principle of the hotbed.

7. Which will be cooler on a hot day, a white hat or a black one?

8. Will tea cool more quickly in a polished or in a tarnished metal vessel?

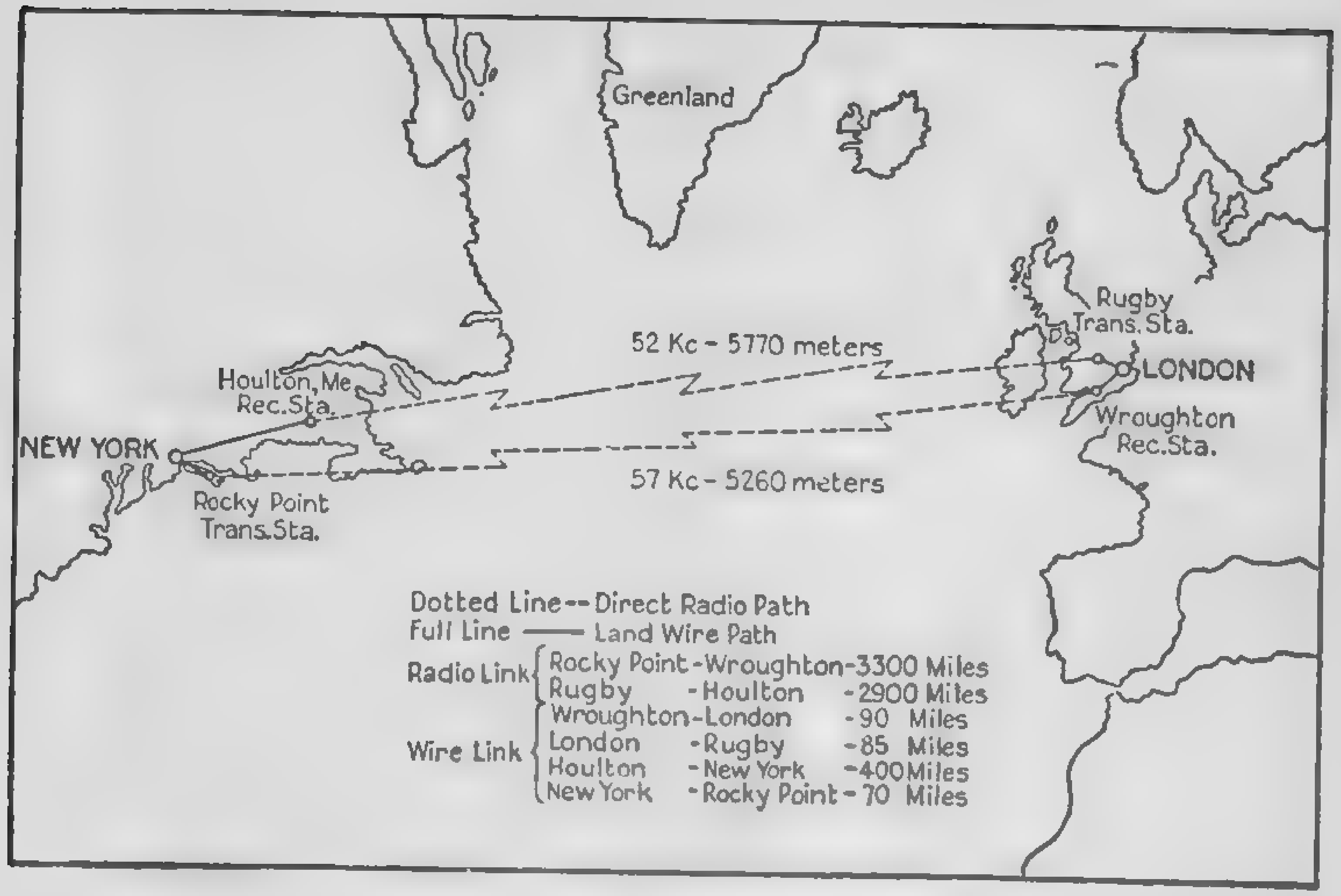
9. In your opinion which would be the more efficient, a polished, nickel-plated steam radiator or a rough, dark one? Explain.

HEINRICH RUDOLPH HERTZ (1857–1894)

One of the most brilliant of German physicists, who, in spite of his early death at the age of thirty-seven, made notable contributions to theoretical physics, and left behind the epoch-making experimental discovery of the electromagnetic waves predicted by Maxwell. Wireless telegraphy is merely an application of this discovery

GUGLIELMO MARCONI (1874–)

The inventor of commercial wireless telegraphy was born in Bologna. He was educated in Leghorn and in the University of Bologna. In 1899, when he was twenty-five years old, he communicated between France and England by wireless. Two years later at Poldhu, Cornwall, he received signals from St. John's, Newfoundland, a distance of 2100 miles



MAP OF TRANSATLANTIC RADIO-TELEPHONE TESTS

Following the early work of 1915 (see opposite page 466) thousands of tests and experiments were made in an effort to place transatlantic radio speech communication on a commercial basis. Finally, on March 7, 1926, by use of 100 kilowatts of power, speech communication between New York and London was maintained both ways for more than four hours, voices being easily recognized. Commercial service began on January 7, 1927. When there is day upon the entire Atlantic, or night only, the difficulties are not so tremendous, but at times there are influences (sunset, for example) that would require many thousands of times the power to maintain communication. Complete commercial success will have been attained when, for example, New York City business houses can with absolute certainty call up and communicate with business firms in London and Paris at any time of day. At present this is not always possible, but the difficulties are probably not insurmountable. In transatlantic radio telephony the present practice (1927) is to use double modulation at the transmitting end. The voice frequency modulates a 33-kilocycle frequency, and the product then modulates a 70-kilocycle to 103-kilocycle carrier. The modulated product goes through an intermediate amplifier, and three stages of high-power amplification. At the American receiving end the process is reversed, the received signal being demodulated, amplified, demodulated again, and then amplified once more. At the English end the process is similar except that single demodulation only is used (see opposite page 460)

10. The atmosphere is transparent to most of the sun's rays. Why are the upper regions of the atmosphere so much colder than the lower regions?

11. Liquid-air flasks and vacuum bottles are double-walled glass vessels with a vacuum between the walls. Liquid air will keep many times longer if the glass walls are silvered than if they are not. Why? Why is the space between the walls made a vacuum?

ELECTRICAL RADIATIONS

482. Proof that the discharge of a Leyden jar is oscillatory. We found in § 408, p. 374, that the sound waves sent out by a sounding tuning fork will set into vibration an adjacent fork, provided the latter has the same natural period as the former. Following is the complete electrical analogy of this experiment:

Let the inner and outer coats of a Leyden jar A (see Fig. 463) be connected by a loop of wire $cdef$, the sliding crosspiece de being arranged so that the length of the loop may be altered at will. Also let a strip of tin foil be brought over the edge of this jar from the inner coat to within about 1 millimeter of the outer coat at C. Let the two coats of an exactly similar jar B be connected with the knobs n and n' by a second similar wire loop of fixed length. Let the two jars be placed side by side with their loops parallel, and let the jar B be successively charged and discharged by connecting its coats with a static machine or an induction coil. At each discharge of jar B through the knobs n and n' a spark will appear in the other jar at C, provided the crosspiece de is so placed that the areas of the two loops are equal. When de is slid along so as to make one loop considerably larger or smaller than the other, the spark at C will disappear.

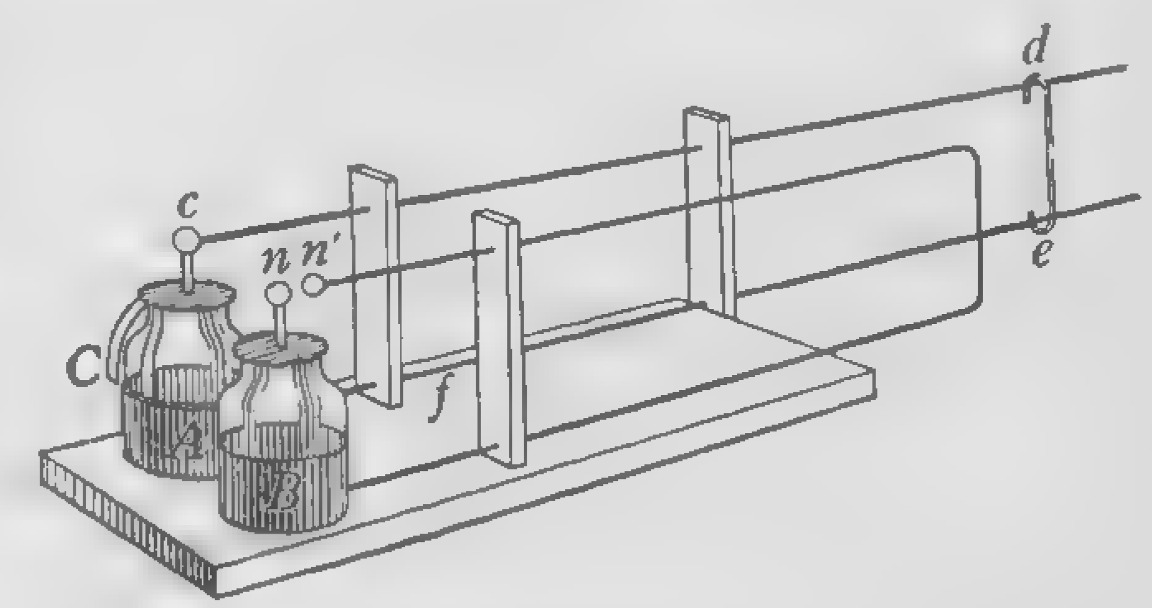


FIG. 463. Sympathetic electrical vibrations

The experiment therefore demonstrates that two electrical circuits, like two tuning forks, can be *tuned* so as to respond to each other sympathetically, and that just as the tuning forks will cease to respond as soon as the period of one is slightly altered, so this *electric resonance* disappears when the exact symmetry of the two circuits is destroyed. Since, obviously, this phenomenon of resonance can occur only between systems which have *natural periods* of vibration, the experiment proves that the discharge of a Leyden jar is a vibratory, that is, an oscillatory, phenomenon. As a matter of fact, when such a spark is viewed in a rapidly revolving mirror, it is actually found to consist of from ten to thirty flashes following each other at equal intervals. Fig. 464 is a photograph of such a spark.

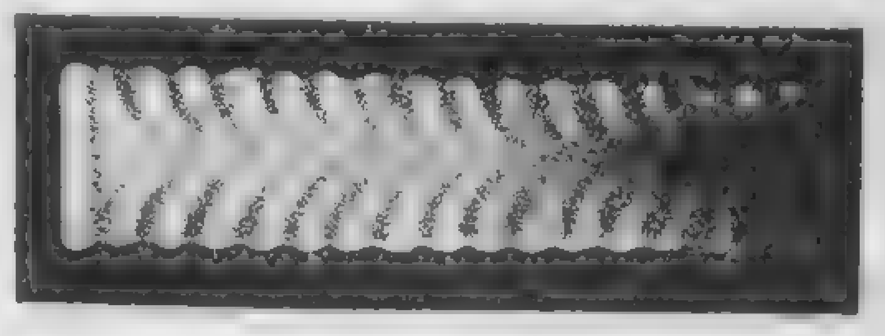


FIG. 464. Oscillations of the electric spark

In spite of these oscillations the whole discharge may be made to take place in the incredibly short time of $\frac{1}{1,000,000}$ of a second. This fact, coupled with the extreme brightness of the spark, has made possible the surprising results of so-called *instantaneous electric-spark photography* (see opposite pages 258 and 419). The plate opposite page 419 shows the passage of a bullet through a soap bubble. The illuminating flash was so nearly instantaneous that the outlines are not blurred.

483. Electric waves. The experiment of § 482 demonstrates not only that the discharge of a Leyden jar is oscillatory but also that these electrical oscillations set up in the surrounding medium disturbances, or waves of some sort, which travel to a neighboring circuit and act upon it precisely as the air waves acted on the second tuning fork in the sound experiment. Whether these are waves in the air, like sound waves, or disturbances in the ether, like light waves, can be determined by measuring their velocity of propagation. The first determination of this velocity was made by Heinrich Hertz

(see opposite page 454) in 1888. He found it to be precisely the same as that of light, that is, 300,000 kilometers per second. *This result shows, therefore, that electrical oscillations set up waves in the ether.* These waves are now known as Hertz waves.

The length of the waves emitted by the oscillatory spark of instantaneous photography is evidently very great, namely, about 300,000,000/10,000,000, or 30 meters, since the velocity of light is 300,000,000 meters per second, and since there are 10,000,000 oscillations per second; for we have seen in § 383, p. 350, that wave length is equal to velocity divided by the number of oscillations per second. By diminishing the size of the jar and the length of the circuit the length of the waves may be greatly reduced. Waves such as these, however, are millions of times longer than any visible light waves. By causing the electrical discharges to take place between two balls only a fraction of a millimeter in diameter, instead of between the coats of a condenser, electrical waves have been obtained as short as .3 millimeter, — quite as short as the longest measured heat waves.

484. Detection of electric waves. In the experiment of § 482 we detected the presence of the electric waves by means of a small spark gap C in a circuit almost identical with that in which the oscillations were set up. The visible spark may be employed for the detection of waves many feet away from the source, but for detecting the feeble waves which come in from a source hundreds or thousands of miles away we must depend upon sounds produced in an extremely sensitive telephone receiver, as explained in the next section.

485. Wireless telegraphy. Commercial wireless telegraphy was realized in 1896 by Marconi (see opposite page 454), eight years after the discovery of Hertz waves. The essential elements of a tuned *wave-train*, or "spark," system of wireless telegraphy are as follows:

The key K at the transmitting station (Fig. 465 (1)) is depressed to allow a current from the alternator A to pass through the primary coil P of a transformer T_1, the frequency of the alter-

nations in practice being usually about 500 cycles per second. The high-voltage current induced in the secondary S charges the condenser C_1 until its potential rises high enough to cause a spark

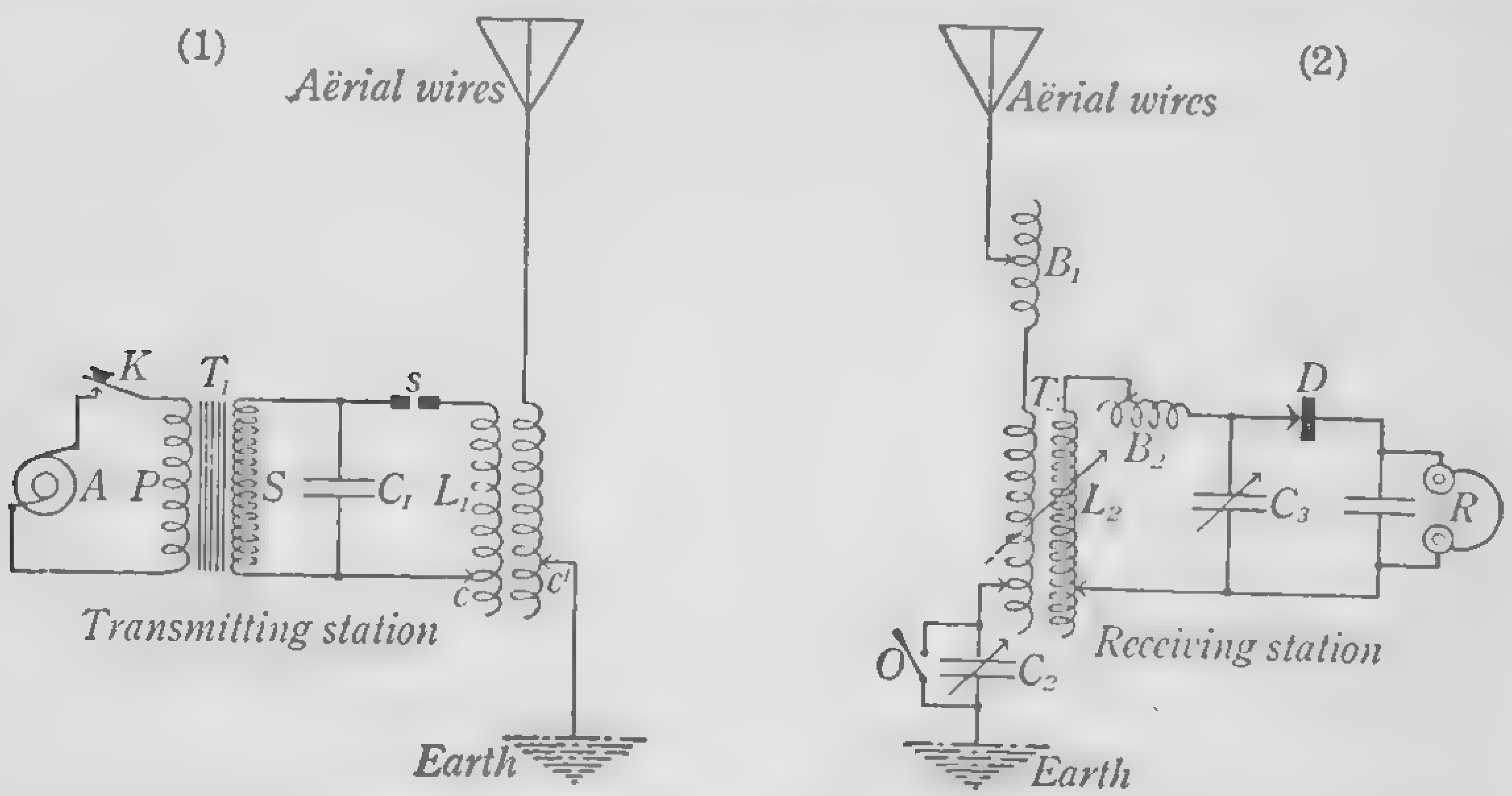


FIG. 465. Transmitting and receiving stations for wireless telegraphy

discharge to take place across the gap s. This discharge of C_1 is oscillatory (§ 482), and the oscillations thus produced in the condenser circuit containing C_1, s, and L_1 may, in a low-power, short-wave transmitting set, have a frequency as high as 1,000,000 per second. An oscillation frequency much lower than this is generally used and is subject to the control of the operator through the sliding contact c, precisely as in the case illustrated in Fig. 463. The oscillations in the condenser circuit induce oscillations in the aërial-wire system, which is tuned to resonance with it through the sliding contact c'.

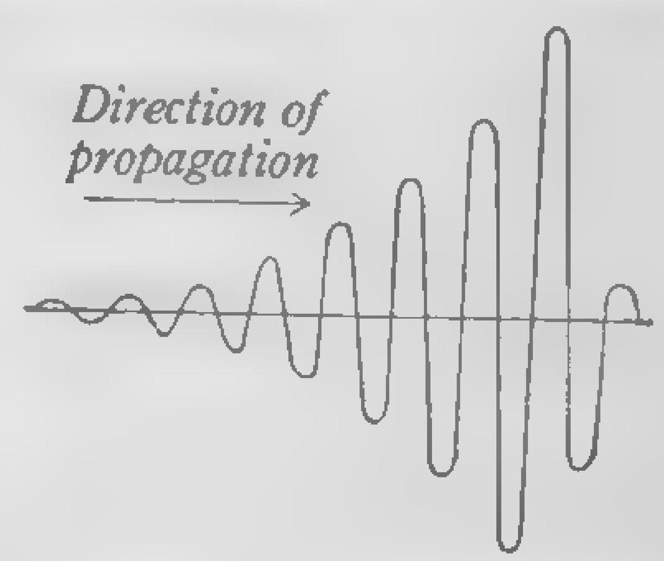


FIG. 466. One wave train from oscillatory discharge

As long as the key K is kept closed (assuming a 500-cycle alternator to be used), 1000 sparks per second occur at s, and therefore a regular series of 1000 wave trains (Fig. 466) pass off from the aërial every second and move away with the velocity of light. If the oscillations which produce a wave train have a frequency of, say, 500,000 per second, each wave in the wave train has a length of 300,000,000/500,000, or 600 meters; and if these wave trains

are produced at the rate of 1000 per second, they follow each other at regular distances of 300,000 meters, that is, nearly 200 miles.

The waves sent out by the aërial system of the transmitting station induce like oscillations in the distant aërial system of the receiving station (Fig. 465 (2)) which is tuned to resonance with it. In case the receiving aërial must be tuned to respond to very long waves, the switch O is closed to cut out the condenser C_2, and the inductance, or loading coil, B_1 is used; whereas, to tune to very short waves, the switch O is opened and the variable condenser C_2 is brought into use, the loading coil not being utilized.* The oscillations in the aërial circuit of the receiving station induce exactly similar ones in the detector circuit, which is tuned to resonance with the receiving aërial by means of L_2, B_2, and C_3. The so-called detector of these oscillations may be simply a crystal of galena D in series with the telephone receivers R. This crystal, like the tungar rectifier of § 375, has the property of transmitting a current in one direction only.† Were it not for this property the telephone could not be used as a detector, because its diaphragm cannot vibrate with a frequency of the order of a million; and even if it could, it would produce sound waves far above the limit of hearing. Because of this rectifying property of the crystal the receiver diaphragm is drawn in only once while the oscillations produced by a given wave train last, this effect being produced by the rectified pulsating current which passes in one direction through the receivers and then ceases until the oscillations produced by the next spark arrive. Since one hundred of the intermittent wave trains strike upon the aërial each second, the operator at the receiving station hears *a continuous musical note of this pitch as long as the key K is depressed.* The working of the key, however, as in ordinary telegraphy, breaks the regular series of wave trains into *groups of wave trains,* so that the short and long notes heard in the receivers (Fig. 467) correspond to the dots and dashes of telegraphy.

* In the diagram an arrow drawn diagonally across a condenser indicates that, for the sake of tuning, the condenser is made adjustable. Similarly, an arrow across two circuits coupled inductively, like the primary and secondary of the oscillation transformer T_2, indicates that the amount of interaction of the two circuits can be varied, as, for example, by sliding one coil a longer or shorter distance inside the other.

† Crystal detectors have been largely superseded by three-electrode vacuum tubes for both wireless telegraphy and wireless telephony.

The receiving circuit, when tuned as shown in Fig. 465 (2), is highly *selective*; that is, it will not pick up waves of other periods. The loading coils B_1 and B_2, as well as the two variable condensers C_2 and C_3, are usually omitted from small amateur receiving sets; but when this is done, the receiving set is less selective and less sensitive. The resistance of the receivers is so high, usually from 1000 to 4000 ohms, that they do not interfere with the oscillations of the condenser system, across which they are placed. *The receiving station shown in Fig. 465 (2) may also be used for receiving wireless-telephone messages.*

Although the spark, or wave-train, system of wireless telegraphy was once used almost exclusively, the "continuous wave" system has now almost entirely displaced it. This is because the continuous-wave signals tune more "sharply"; that is, cause less interference to the reception of other stations using slightly different frequencies. Just as sound waves differing slightly in frequency combine to produce the phenomenon of beats (§ 396), so electrical oscillations differing in frequency give, when combined, a "beat effect." For instance, if electrical oscillations of, say, 30,000 per second and 31,000 per second combine, beats will occur at the rate of 1000 per second, which is a frequency within the limit of hearing. The electrical oscillations mentioned above have a frequency beyond the limit of hearing and hence are said to have *radio* frequency; but the beats, being within the range of hearing, have an *audio* frequency. Now let us assume that there is at the transmitting station an alternating-current generator which throws into the aërial powerful undamped oscillations of 30,000 per second; and suppose further that at the receiving station there is an oscillation generator which maintains relatively weak oscillations of 31,000 per second in the local receiving

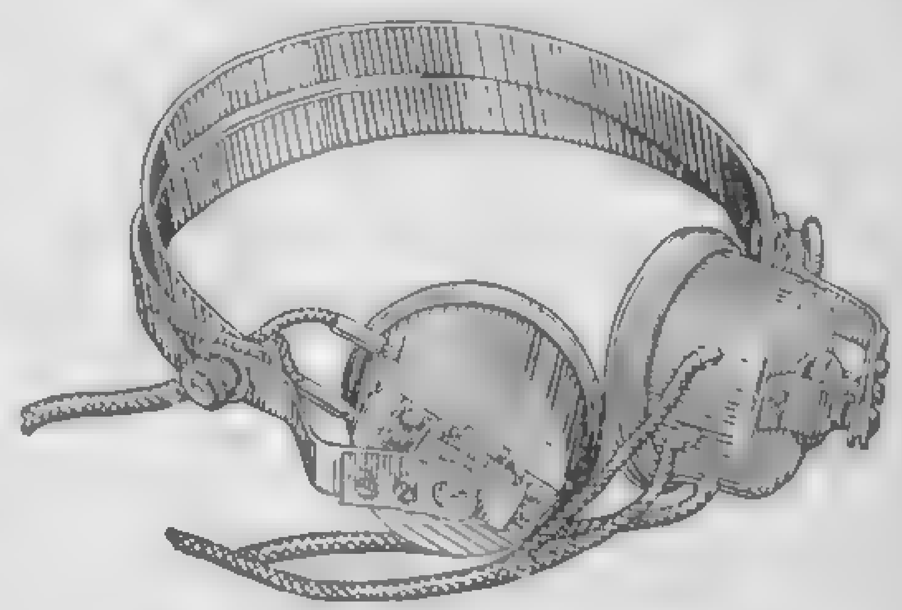
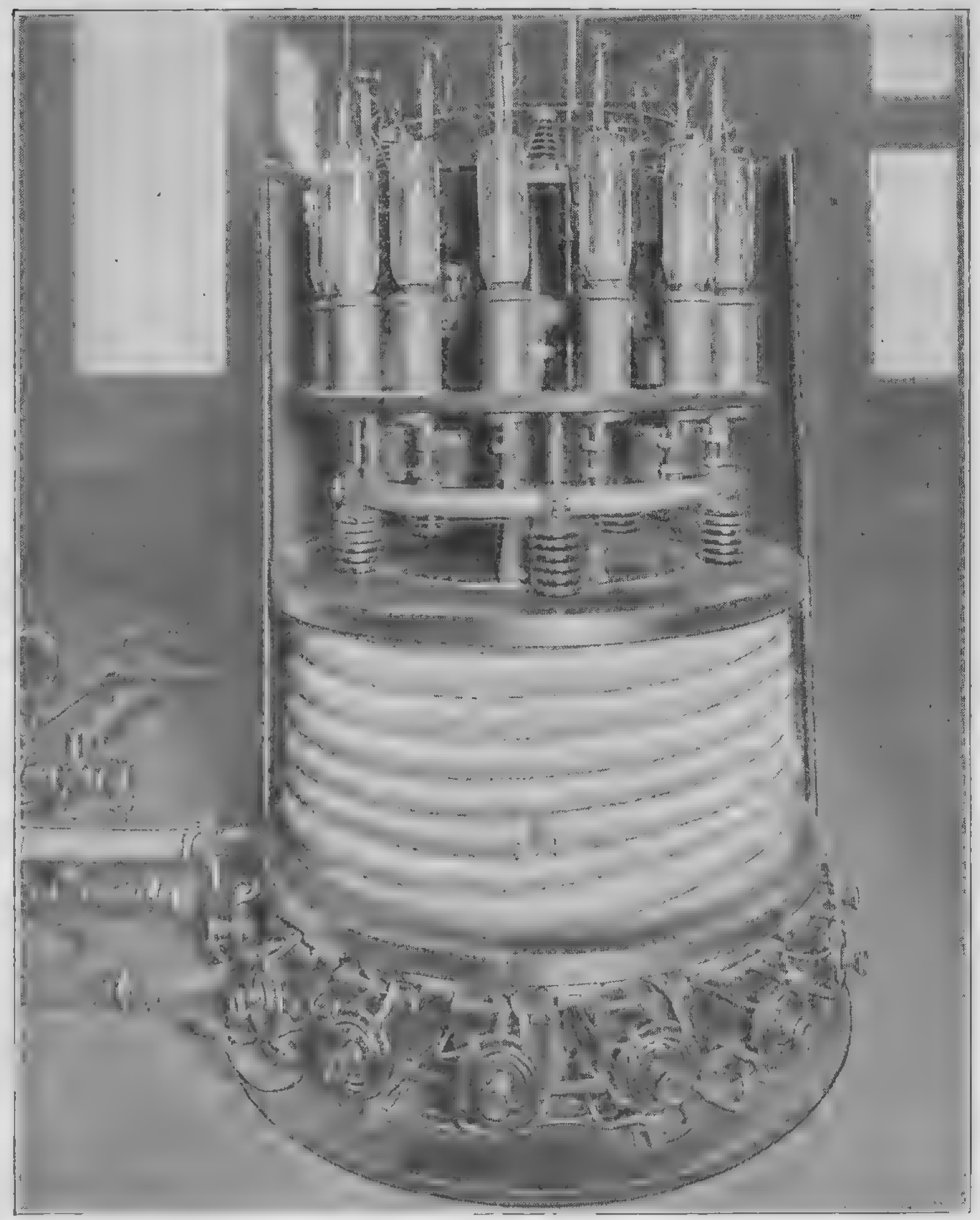


FIG. 467. United States navy standard radio receivers



A BANK OF FIFTEEN WATER-COOLED POWER AMPLIFIER TUBES

This picture shows fifteen 10-kilowatt vacuum tubes connected in parallel. This bank of tubes was used in the last stage of the transmitting equipment at Rocky Point, New York, during the transatlantic radio-telephone tests in March, 1926 (see opposite pages 455 and 466). The large coil of rubber tubing carries water to and from the tubes; at the same time it is long enough to act as an insulator for the plates, which have a 10,000-volt potential. The resistance of the water column is well over 100,000 ohms

THE WIRELESS TELEPHONE UTILIZED IN AVIATION

One of the most notable developments of the war was the directing of a squadron of airplanes in intricate maneuvers by wireless telephone either from the ground or by the commander in the leading plane. The upper panel shows the pilot and the observer conversing with special apparatus designed to eliminate plane noises, and the lower panel shows President Wilson talking by wireless to airplanes

aërial. These weak oscillations produced in the receiving aërial by the local generator make no sound in the receiver, being above the limit of hearing; but *whenever, and as long as*, the operator at the transmitting station depresses his key, waves come in at the rate of 30,000 per second, strike against the receiving aërial and develop therein weak oscillations, which combine with those already present to make 1000

FIG. 468. A series of wave trains

beats per second. These beat effects are rectified by a crystal or by a vacuum tube and passed through the receiver. The listener, therefore, hears long and short musical sounds, just as he does when receiving by the spark system. The beat method of receiving is called the heterodyne system.

486. Modulated continuous waves.* The vibrations constituting articulate speech are exceedingly complex, as may be seen from an inspection of the full-page halftone opposite page 372. Because of this complexity it is impossible to transmit speech by means of discontinuous waves (Fig. 468) such

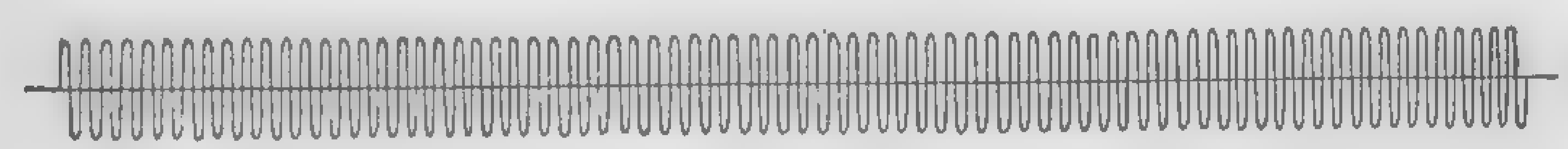


FIG. 469. Continuous, or carrier, waves of radio frequency

as are employed in the system of spark telegraphy described in the preceding section. The parts of the voice lost because of the gaps between the wave trains would render the language unintelligible. Therefore, speech is transmitted on continuous, or "carrier," waves (Fig. 469) having a frequency (radio frequency) above the limit of hearing.

At the sending station the continuous waves (Fig. 469) are "modulated" by the voice at the transmitter; that is,

* The pupil should master §§ 375, 376, 377, 482, 483, 484, and 485 before reading the six sections following.

the sound waves of the voice act upon the apparatus in such a way as to alter the otherwise uniform amplitude of the series of continuous waves (Fig. 470). These modulated continuous waves on reaching the aërial of the receiving station produce

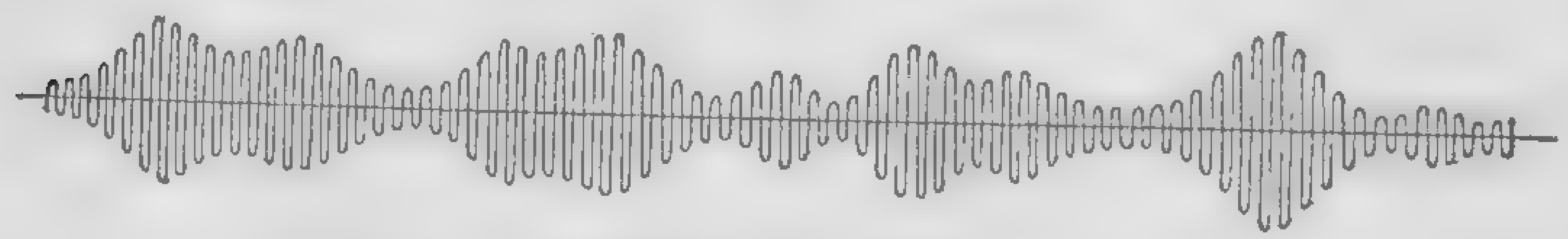


FIG. 470. Modulated radio-frequency waves

corresponding oscillatory currents in the wires of the aërial. By means of a crystal or a vacuum tube, the oscillatory currents are rectified into a series of *undirectional* electrical currents, or pulses, somewhat after the manner indicated in

FIG. 471. Rectified oscillations

Fig. 471. These variable pulses of radio frequency, on reaching the telephone receivers of the listener, produce diaphragm vibrations of low frequencies (audio frequencies), which rarely go outside the limits of 100 and 3000 vibrations per second.

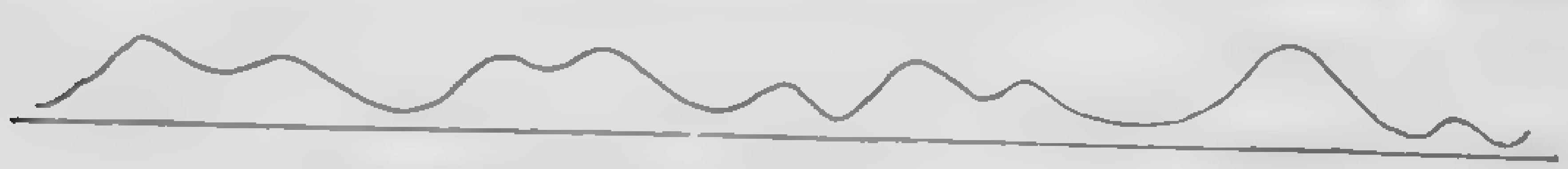


FIG. 472. Audio-frequency variations

They are represented by the irregular line in Fig. 472. The vibrations of the diaphragms of the receivers, therefore, correspond to the vibrations of the voice of the speaker at the distant transmitting station.

487. Method of producing continuous waves. One of several important devices for producing high-power continuous waves is the Alexanderson high-frequency alternator. This is an alternating-current dynamo made in various powers up to 200 kilowatts (= 268 H. P.), the rotor in some of the machines having the very high speed of 20,000 revolutions per minute.

For transoceanic telegraphy these machines cause currents of from 600 to 1200 amperes to oscillate in the sending aërial. This powerful sustained oscillation of electrons in an aërial produces continuous electromagnetic waves (Fig. 469).

The Poulsen arc and especially the high-power vacuum tube are widely used for the generation of continuous waves.

488. The vacuum tube. There are several devices by which the voice waves may modulate the carrier waves, the most important being the highly exhausted "vacuum tube" (Fig. 473). F is the *filament* in the center, G the *grid* surrounding the filament and P the *plate* (front half cut away) surrounding the grid. (See opposite pages 460 and 467.)

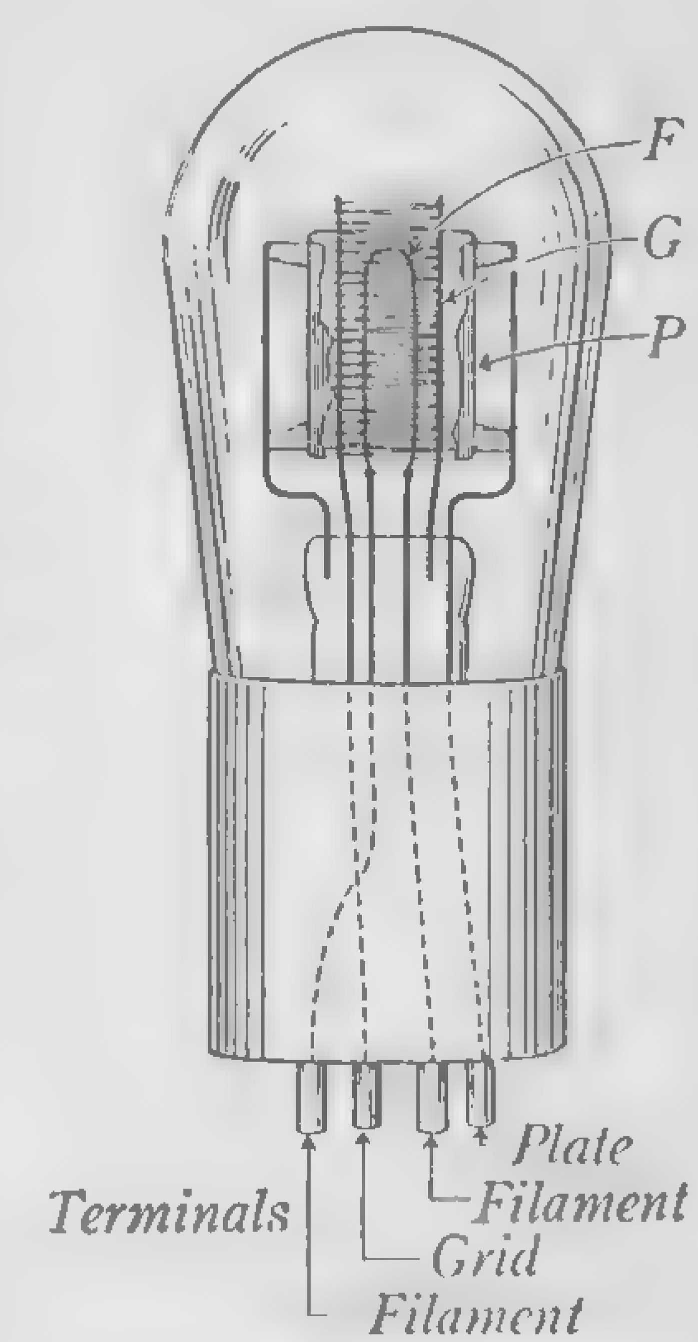


FIG. 473. A popular form of vacuum tube used in radio receiving

In attempting to reach an understanding of a vacuum tube, remember that a current of electricity is a stream of negative electrons which, when passing through a vacuum, move with enormous velocity (thousands of miles per second (§ 494)), but when passing along a wire (ordinary conduction) move quite slowly (a few centimeters per second). Now we found in studying the tungar rectifier (§ 375) that these negative electrons escape freely from an incandescent filament under certain conditions. When the battery B (Fig. 474) has its + terminal connected to the plate P of the vacuum tube and its − terminal to the filament F, no current can flow across the vacuum as *long as the filament is cold.* When, however, the filament is maintained at incandescence by a battery A, the negative electrons escape from it and are drawn in a steady stream across the vacuum by the attraction of the + plate P. This flow of − electrons from filament to plate constitutes

what is considered by convention to be a current of electricity flowing the opposite way, namely, from plate to filament. We now see how battery A, by keeping the filament in a state of incandescence, merely establishes and maintains one of the conditions under which battery B may discharge a steady current through the vacuum. No electronic flow from the cold plate to the filament is ever possible, because cold bodies do not, except in rare instances (see pages 475 ff.) eject electrons from themselves. The vacuum tube can therefore be utilized as a vacuum *valve*, or rectifier, for obviously, if a source of alternating current is substituted for the direct-current source (battery B), the vacuum valve would transmit current in one direction only, half of each cycle being held in check.

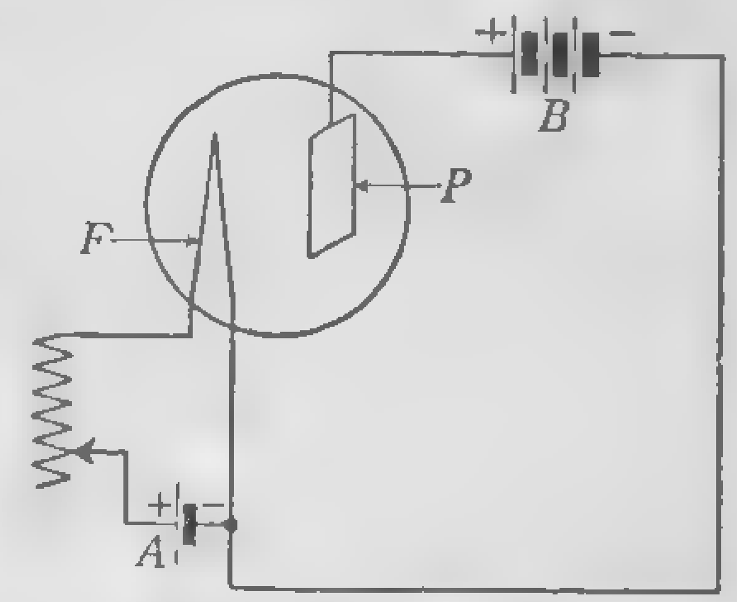


FIG. 474. A two-electrode vacuum tube

If a screen of fine wire G, known as a "grid," be introduced between the filament and the plate of Fig. 474 (see Fig. 475) *and the grid be maintained at a sufficiently high — potential* by a battery C, the — electrons are repelled into the incandescent filament and cannot escape from it, and thus the electronic flow is completely checked; that is, *no current flows across the vacuum.* If now the — potential of the grid be varied, say, from zero to the amount required to stop the electronic flow, the current from battery B through the vacuum is thereby varied from the possible maximum in Fig. 474 to zero. Variation of the grid potential, therefore, affords us a means of controlling and of varying the flow of current

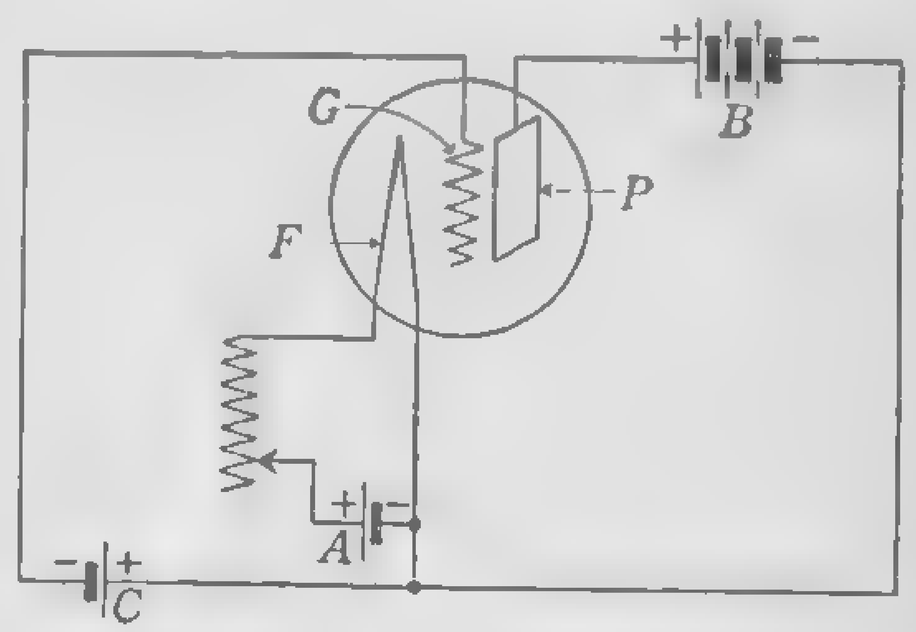


FIG. 475. A three-electrode vacuum tube

through a vacuum tube. Indeed, it is found that *slight* changes in the grid voltage produce surprisingly *great* changes in the current through the tube; that is, the tube is an *amplifier*.

489. The receiving station. Fig. 476 represents a *regenerative* receiving circuit capable of receiving long or short waves. When the modulated waves (Fig. 470) reach the tuned aërial of the receiving station, they develop therein feeble electrical oscillations which induce oscillations in L_2

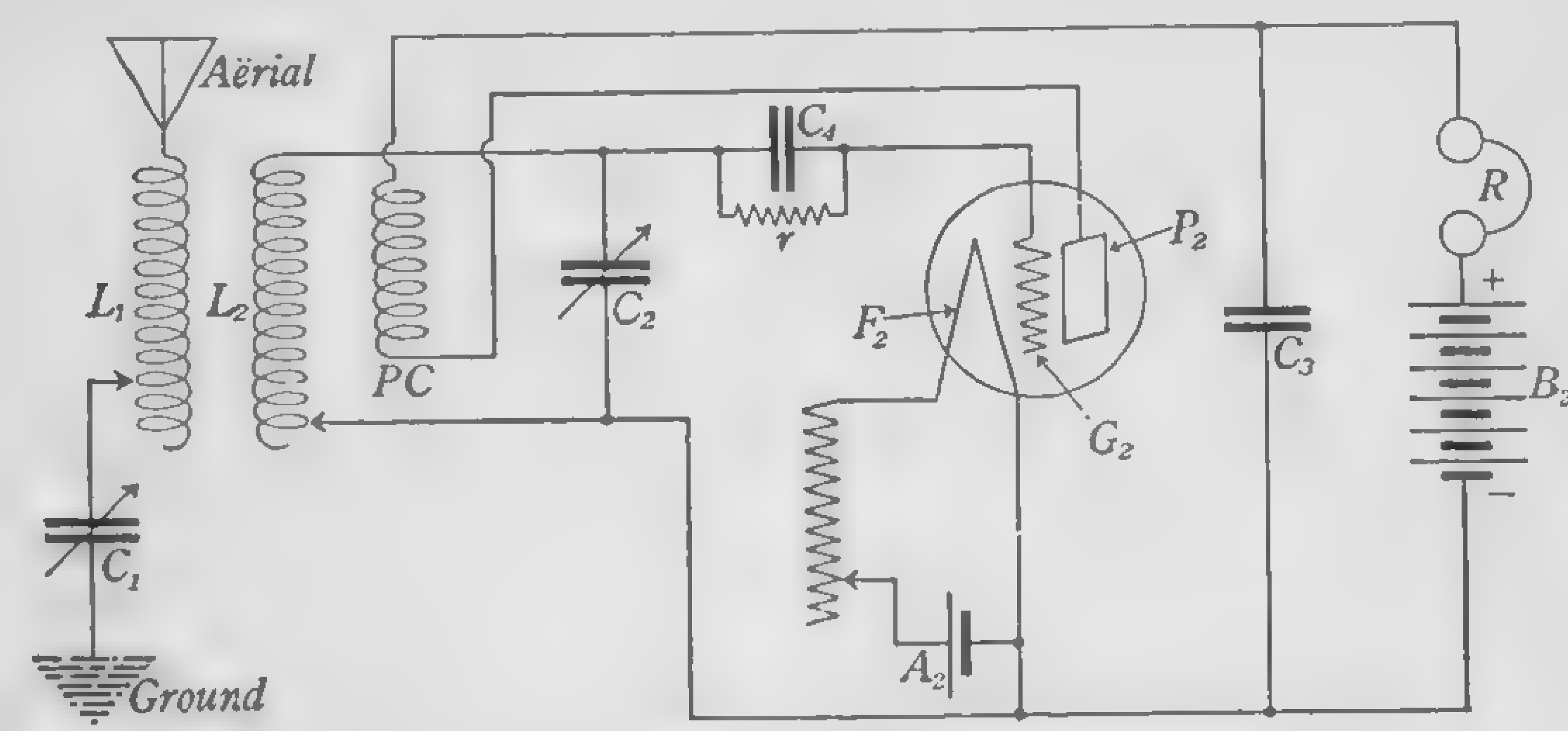


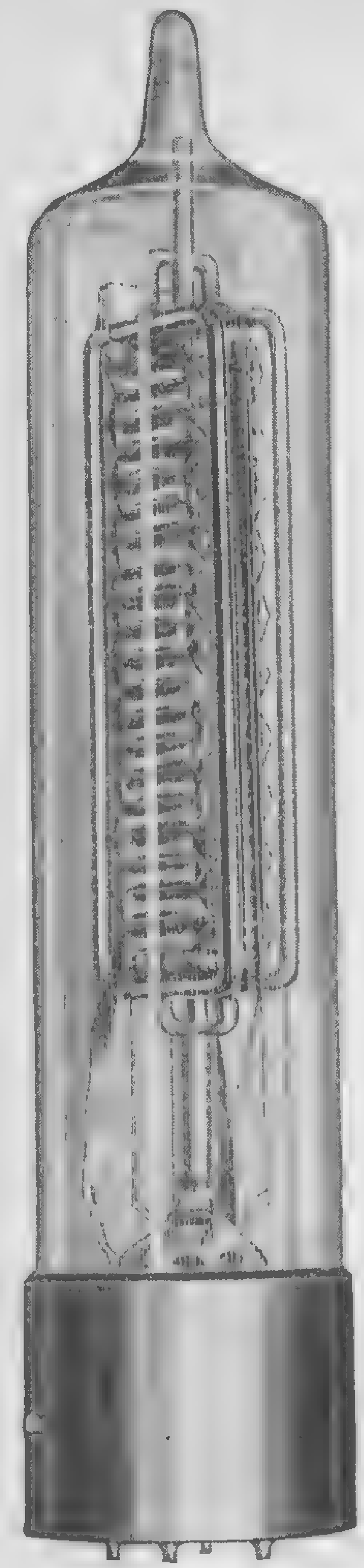
FIG. 476. A regenerative receiving circuit

of the tuned grid circuit. This varies the potential of the grid G_2, thus causing corresponding changes in the strength of the electronic current flowing from the incandescent filament F_2 to the plate P_2 and thence back through the plate coil PC, or *tickler*. The plate circuit is so tuned with respect to the grid circuit that these current variations in the plate coil react inductively on the coil L_2 connected with the grid circuit to strengthen the original grid-circuit current. This intensifies the variations in potential at the grid, which in turn intensifies the variations in strength of the electronic current from filament to plate, and this still further intensifies the variations in potential at the grid, and so on, up to the limit of the electron supply in the tube. This is the *Armstrong regenerative principle*, by which very feeble oscilla-

tions produced by the incoming waves may be amplified and then used to intensify the original oscillations. *The energy for regeneration comes from the battery B_2.* When the tube is in use the grid tends to accumulate a negative charge which, as we have seen (§ 488), would tend to block completely the action of the tube. Therefore, a high-resistance grid leak r is shunted around the condenser C_4 to permit the return of such a detrimental accumulation of electrons to the filament F_2 by way of r and L_2. The telephone receivers used in wireless work contain thousands of turns of very fine wire wound upon iron and because of the consequent *choke-coil* effect, or impedance, of these coils for *high-frequency* changes in current strength, the *radio*-frequency variations (Fig. 471) of the plate current pass largely by way of the condenser C_3, whereas the slower *audio*-frequency variations (Fig. 472) of the plate current pass readily through the receivers to actuate the diaphragm.

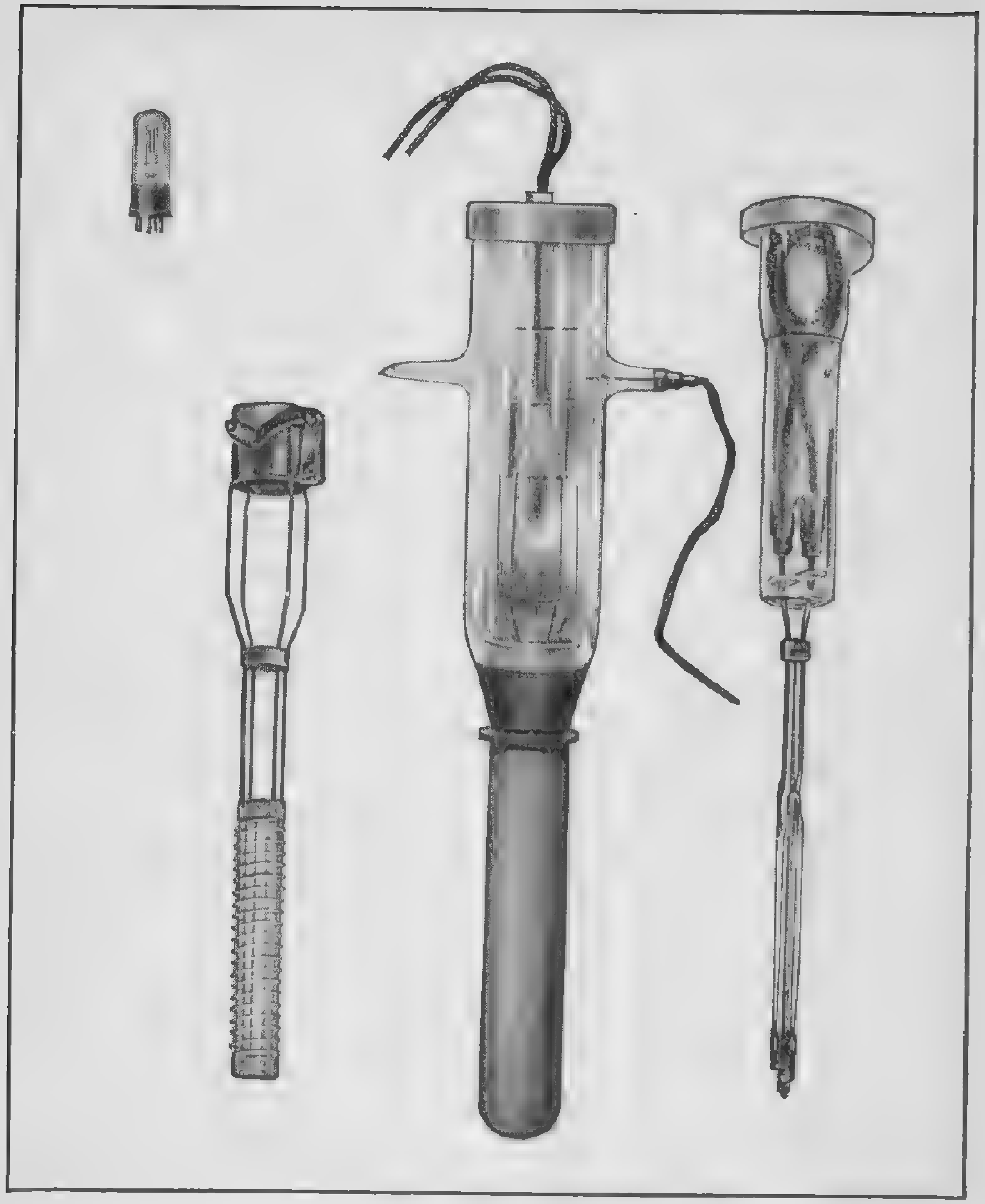
Receiving sets are now so numerous that the use of the circuit of Fig. 476 is being discouraged. This is because such a circuit is frequently made to oscillate, and the receiving set then becomes a small transmitting station. The waves sent out from the aërial are very weak, but are nevertheless distinctly audible in other neighboring receiving sets. This causes annoying interference with the reception of broadcast programs.

Fig. 477 shows a receiving circuit that does not oscillate, yet gives amplification of the received waves through the use of three vacuum tubes instead of one. As in Fig. 476, the oscillations set up between the aërial and ground induce similar oscillations in the grid circuit of T_1, this circuit being tuned by means of C_5. T_1 has no grid condenser (like C_4 of Fig. 476), and in its plate circuit is the coil L_5 instead of telephone receivers. This coil has a low impedance, hence radio-frequency oscillations flow through it, much stronger than those in the grid circuit. T_1 thus becomes a *radio-frequency amplifier*. The oscillations in L_5 induce similar ones in L_6



The extraordinary developments in electronics have had commercial consequences, of which the following are perhaps the most significant: In July, 1914, through the development of the De Forest audion into a distortionless telephone relay and amplifier, and the insertion of these amplifiers into suitably chosen places in the telephone line between San Francisco and New York, the research physicists of the Western Electric Company were able to give numerous demonstrations in which audiences in New York and Boston were able to hear with perfect distinctness the splashing of the waves in the San Francisco harbor. By the summer of 1915 the same group of men had succeeded in throwing telephonic speech up into the antennæ of the wireless station at Arlington with such intensity that it traveled without wires a third of the way around the world and was heard so distinctly at receiving stations in both Honolulu and Paris that even the voices of the speakers in Washington could be recognized. The illustration at the left is a cut (about $\frac{1}{3}$ size) of one of the tubes with which this extraordinary scientific feat was performed. By the use of these devices the enormous energy amplifications of 10,000,000,000,000-fold have been obtained

VACUUM TUBE USED IN EARLY EXPERIMENTS IN WIRELESS TELEPHONY



COMPARISON OF DRY-CELL TUBE WITH WATER-COOLED POWER TUBE

The picture shows the relative sizes of a dry-cell detector tube and a huge water-cooled power tube capable of giving a net output into the antenna of 20 kilowatts. The small tube works normally with a current of .25 ampere at 1.1 volts through the filament and with .0028 ampere (2.8 milliamperes) at $22\frac{1}{2}$ volts between filament and plate; the power tube operates with a filament current of 52 amperes at 22 volts and a plate current of 2 amperes oscillating at 15,000 volts. The filament and grid of the large tube are shown to the right and left, respectively, of it

and the grid circuit of T_2, which is tuned by means of C_6. T_2 acts like the tube of Fig. 476, except that the regenerative coil, PC, is not used. T_2 is called the *detector* or *rectifier*, because it changes the radio-frequency oscillations to audio-frequency pulses, as explained in § 486. These audio-frequency pulses flow through the primary of the audio-frequency transformer, AFT. This transformer has an iron core, as indicated by the vertical lines between the coils. The secondary of AFT is connected to the grid of T_3, which then

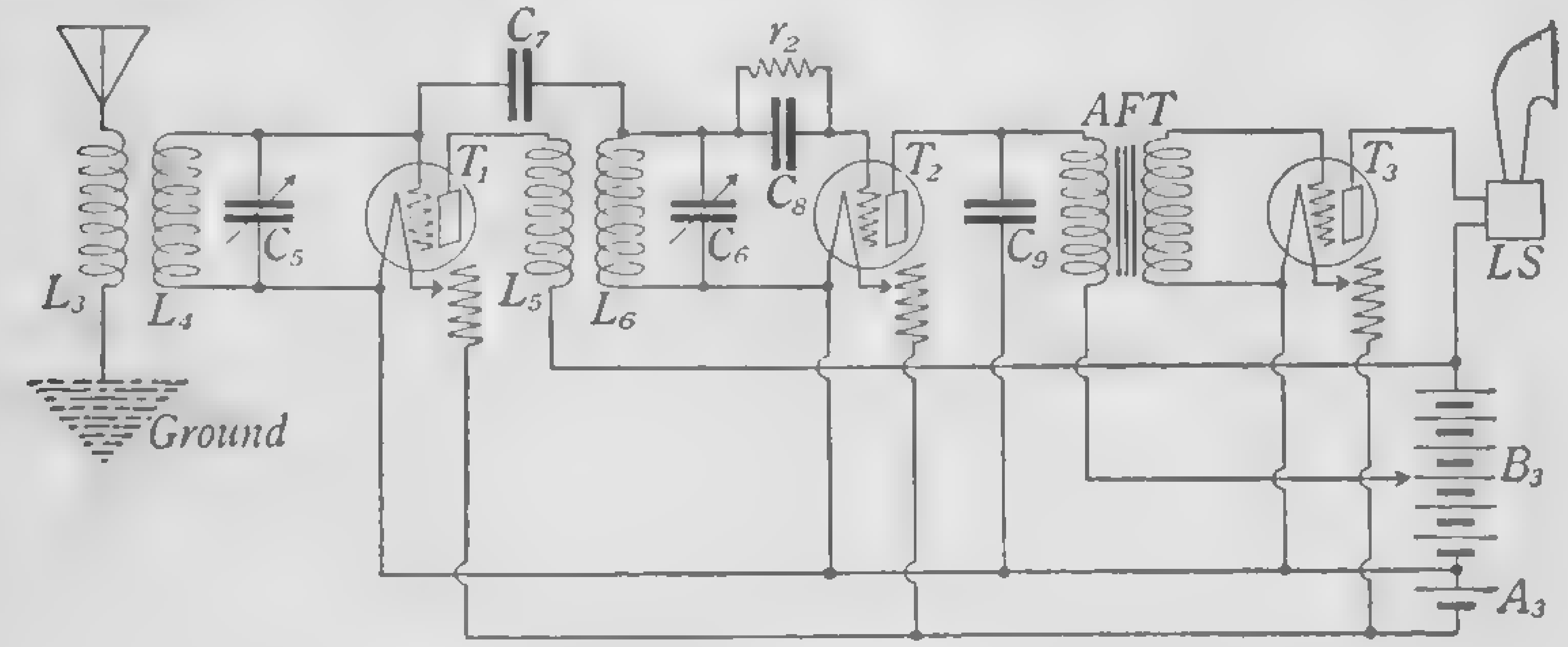


FIG. 477. Receiving circuit using radio-frequency and audio-frequency amplifiers

becomes an *audio-frequency amplifier.* That is, the audio-frequency pulses coming to the grid of T_3 cause similar, but much stronger, pulses to flow in the plate circuit. They may be even strong enough to operate the loud speaker, LS, and thus be heard in all parts of the room. The same filament battery, A_3, and plate battery, B_3, are used for all the tubes, except that only a part of B_3 is used for the detector tube. The grid and plate of a vacuum tube act as a very small condenser. Although this does no harm in T_2 and T_3, it has an undesirable effect in T_1. This effect is neutralized by the small condenser C_7, which has given the name "neutrodyne" to the circuit. It is possible to use several radio-frequency and several audio-frequency amplifiers, thus increasing still further the loudness of the sounds produced.

Many other receiving circuits ("reflex," "superheterodyne," etc.) are in use at the present time.

490. The transmitting station. The vacuum tube may be used not only as a rectifier, a detector, a modulator, and an amplifier, but under certain conditions as a *generator of oscillations* varying over an extremely wide range of frequency — from less than 1 oscillation per second to 300,000,000 or more per second. Nearly all present-day broadcasting is done by use of vacuum-tube generators. For high-power long-distance transmission *banks* of vacuum-tube amplifiers (see opposite page 460) may be used to throw into an aërial an aggregate power of many hundreds of kilowatts. Indeed, at the present time rapid progress is being made in the experimental construction of power tubes *each one of which* is capable of giving an amazing output. Power tubes of from 1 to 10 kilowatts each are now in use in about one hundred broadcasting stations. The army and navy are also using them extensively, and one English station is using them for transatlantic telegraphy. These all use the Housekeeper glass-copper seal, with the anode forming part of the wall and water-cooled. A 20-kilowatt tube has been perfected (see opposite page 467) and several of them are being used constantly in experimental transatlantic telephony. A 100-kilowatt tube is being developed. The life of a vacuum tube is generally from 1000 to 5000 hours, whereas a high-frequency alternator, such as the Alexanderson will last for many years.

It is entirely beyond the scope of this book to explain the actual details of a wireless-telephone transmitting station. However, a method used at present in high-power long-distance transmission is indicated in Fig. 478 and may be outlined as follows: Air vibrations produced by the voice make variations in the current of the primary circuit of the telephone transmitter (§ 377). This induces corresponding E.M.F.'s in the secondary circuit, which impresses audio-frequency variations of potential upon the grid of a vacuum-tube modulator. The resulting changes of audio frequency

in the current of the plate circuit of the modulator correspondingly affect the output of the high-frequency oscillation generator. This modulated radio-frequency output is amplified by a bank of three-electrode power tubes and is then delivered to the aërial through an oscillation transformer. Although transoceanic telephonic communication has been successfully and repeatedly accomplished since 1915 (see opposite pages 455 and 466), regular commercial service was not established until January 7, 1927.

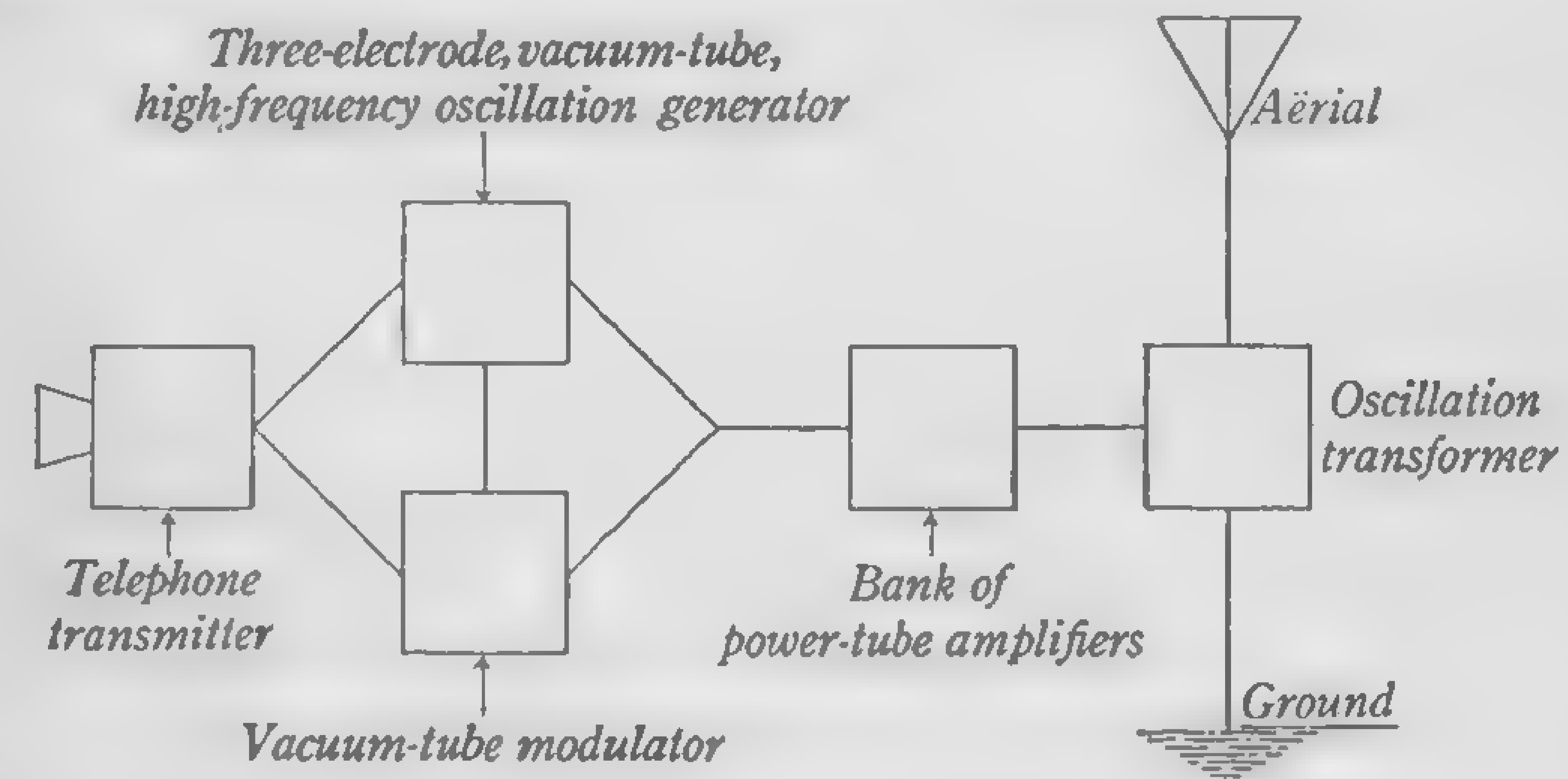


FIG. 478. High-power, long-distance, wireless-telephone transmitting station

491. The electromagnetic theory of light. The study of electromagnetic radiations, like those discussed in the preceding paragraphs, has shown not only that they have the speed of light but that they are reflected, refracted, and polarized; in fact, that they possess all the properties of light waves, the only apparent difference being in their greater wave length. Hence *modern physics regards light as an electromagnetic phenomenon*; that is, light waves are thought to be generated by the oscillations of the electrically charged parts of the atoms. It was as long ago as 1864 that Clerk-Maxwell, (see opposite page 55), of Cambridge, England, one of the world's most brilliant physicists and mathematicians, showed that it ought to be possible to create ether waves by means

of electrical disturbances. But the experimental confirmation of his theory did not come until the time of Hertz's experiments (1888). Maxwell and Hertz together, therefore, share the honor of establishing the modern electromagnetic theory of light.

Cathode and Röntgen Rays

492. The electric spark in partial vacua. Let a and b (Fig. 479) be the terminals of an induction coil or static machine; e and f, electrodes sealed into a glass tube 60 or 80 centimeters long; g, a rubber tube leading to an air pump by which the tube may be exhausted. Let the coil be started before the exhaustion is begun. A spark will pass between a and b, since ab is a very much shorter path than ef. Then let the tube be rapidly exhausted. When the pressure has been reduced to a few centimeters of mercury, the discharge will be seen to choose the long path ef in preference to the short path ab, thus showing that *an electrical discharge takes place more readily through a partial vacuum than through air at ordinary pressures.*

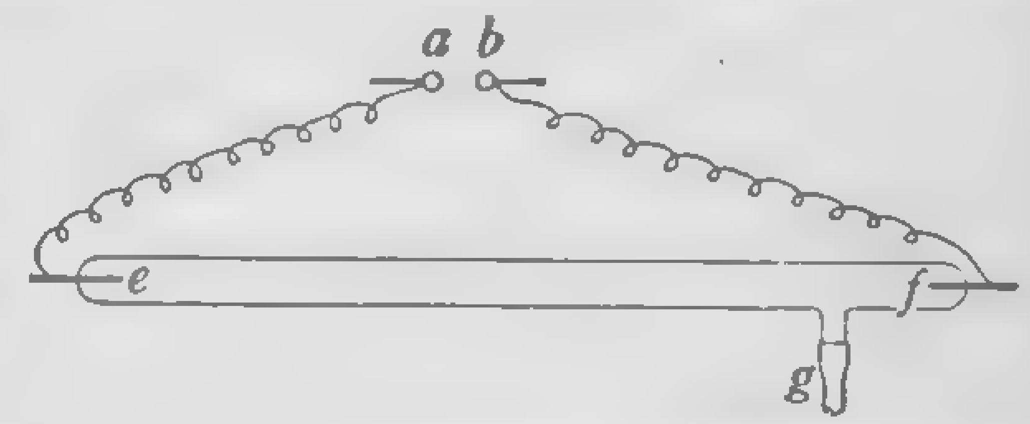


Fig. 479. Discharge in partial vacua

When the spark first begins to pass between e and f it will have the appearance of a long ribbon of crimson light. As the pumping is continued this ribbon will spread out until the crimson glow fills the whole tube. Ordinary so-called Geissler tubes are tubes precisely like the one above except that they are usually twisted into fantastic shapes and are sometimes surrounded with jackets containing colored liquids, which produce pretty color effects.

493. Cathode rays. When a tube like the one above is exhausted to a very high degree, say, to a pressure of about .001 millimeter of mercury, the character of the discharge changes completely. The glow almost entirely disappears from the residual gas in the tube, and certain invisible radiations

called *cathode rays* are found to be emitted by the cathode (the terminal of the tube which is connected to the negative terminal of the coil or static machine). These rays manifest themselves, first, by the brilliant fluorescent effects which they produce in the glass walls of the tube, or in other substances within the tube upon which they fall; secondly, by powerful heating effects; and thirdly, by the sharp shadows which they cast.

Thus, if the negative electrode is concave, as in Fig. 480, and a piece of platinum foil is placed at the center of the sphere of which the cathode is a portion, the rays will come to a focus upon a small part of the foil and will heat it white-hot, thus showing that the rays, whatever they are, travel out in straight lines at right angles to the surface of the cathode. This may also be shown nicely by an ordinary bulb of the shape shown in Fig. 482. If the electrode A is made the cathode and B the anode, a sharp shadow of the piece of platinum in the middle of the tube will be cast on the wall opposite A, thus showing that the cathode rays, unlike the ordinary electric spark, do not pass between the terminals of the tube, but pass out in a straight line from the cathode surface.

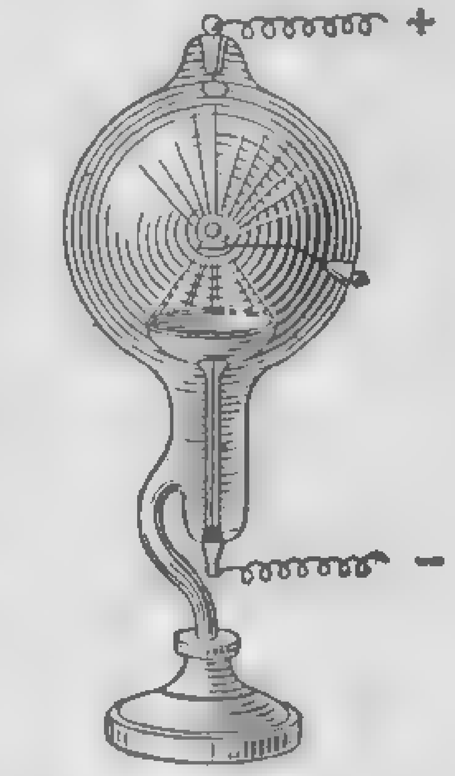


Fig. 480. Heating effect of cathode rays

494. Nature of the cathode rays. The nature of the cathode rays was a subject of much dispute between the years 1875, when they first began to be carefully studied, and 1898. Some thought them to be streams of negatively charged particles shot off with great speed from the surface of the cathode, and others thought they were waves in the ether — some sort of invisible light. The following experiment furnishes very convincing evidence that the first view is correct.

NP (Fig. 481) is an exhausted tube within which has been placed a screen sf coated with some substance like zinc sulphide, which fluoresces brilliantly when the cathode rays fall upon it; mn is a mica strip containing a slit s. This mica strip absorbs all

the cathode rays which strike it; but those which pass through the slit s travel the full length of the tube, and although they are themselves invisible, their path is completely traced out by the fluorescence which they excite upon sf as they graze along it. If a magnet M is held in the position shown, the cathode rays will be seen to be deflected, and in exactly the direction to be expected if they consisted of negatively charged particles. For we learned in § 299, p. 263, that a moving charge constitutes an electric current, and in § 351, p. 316, that an electric current tends to move in an electric field in the direction given by the motor rule. On the other hand, a magnetic field is not known to exert any influence whatever on the direction of a beam of light or on any other form of ether waves.

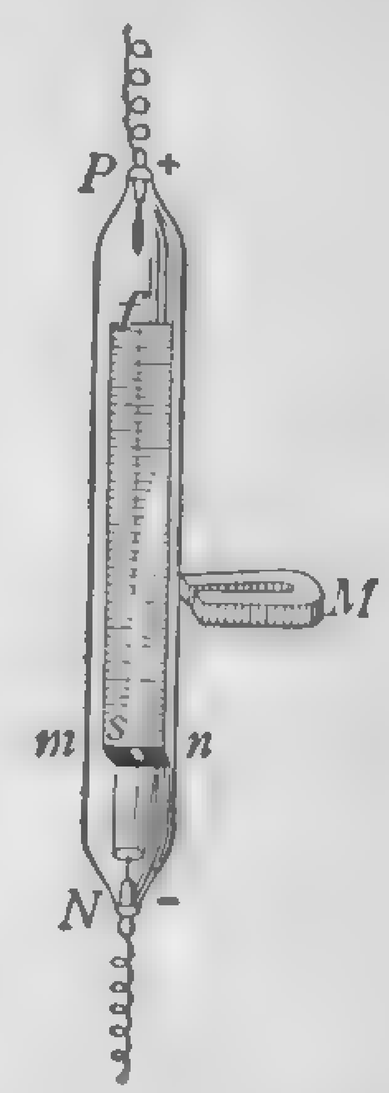
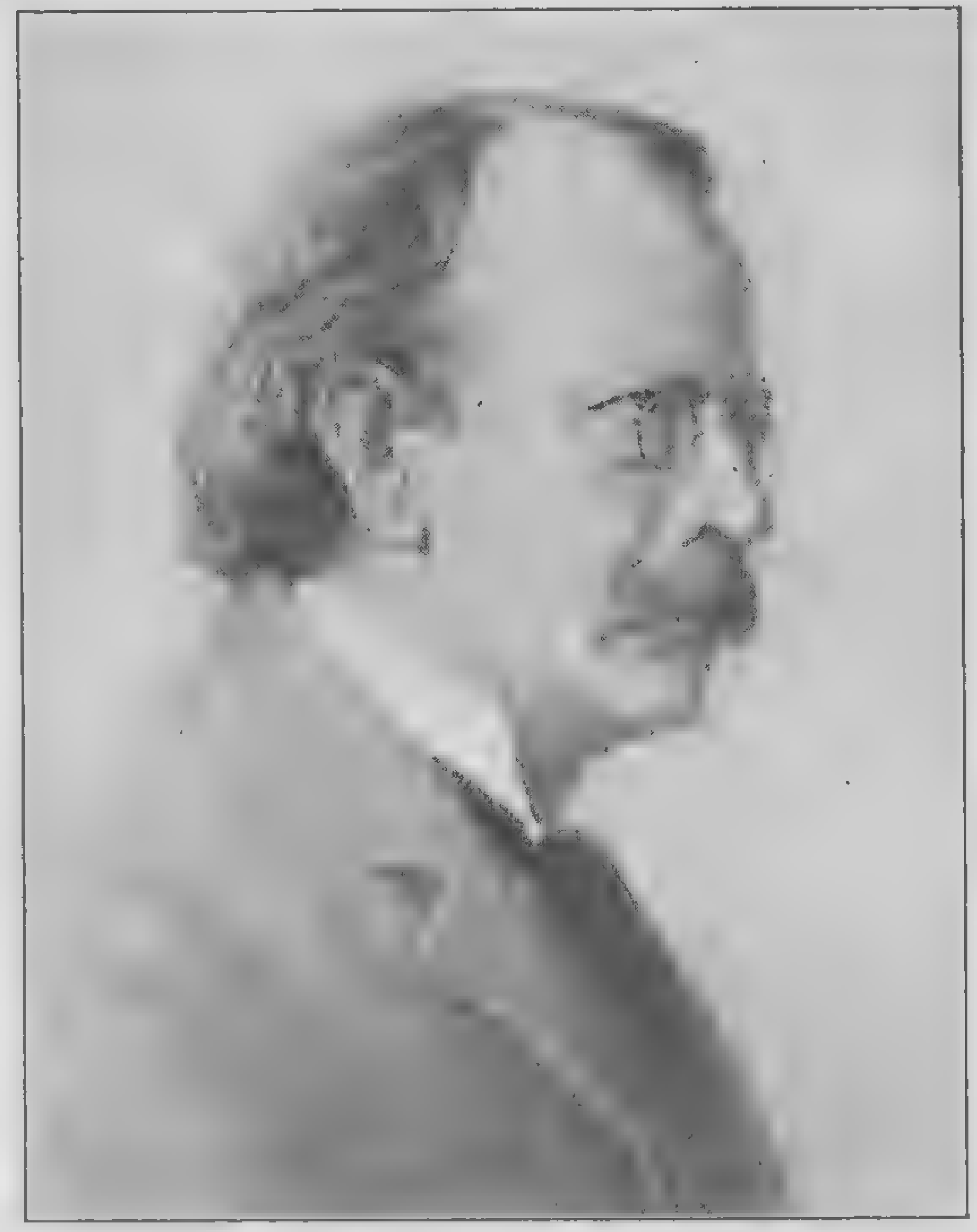


FIG. 481. Deflection of cathode rays by a magnet

When, in 1895, J. J. Thomson (see on opposite page), of Cambridge, England, proved that the cathode rays were also deflected by electric charges, as was to be expected if they consist of negatively charged particles, and when Perrin in Paris had proved that they actually impart negative charges to bodies on which they fall, all opposition to the projected particle theory was abandoned. The mass and speed of these particles are computed from their deflectibility in magnetic and electric fields.

Cathode rays are then today universally recognized as streams of electrons shot off from the surface of the cathode with speeds which may reach the stupendous value of 100,000 miles per second.

495. X rays. It was in 1895 that Röntgen (see opposite page 478) first discovered that wherever the cathode rays impinge upon the walls of a tube, or upon any obstacles placed inside the tube, they give rise to another type of invisible radiation which is now known under the name of *X rays* or *Röntgen rays*. In the ordinary X-ray tube (Fig. 482) a thick piece of platinum P is placed in the center to serve as a tar-



SIR JOSEPH THOMSON (1856–)

Most conspicuous figure in the development of the "physics of the electron"; born in Manchester, England; educated at Cambridge University; Cavendish professor of experimental physics in Cambridge since 1884; author of a number of books, the most important of which is the "Conduction of Electricity through Gases," 1903; author or inspirer of much of the recent work, both experimental and theoretical, which has thrown light upon the connection between electricity and matter; worthy representative of twentieth-century physics

X-RAY PICTURE OF THE HUMAN THORAX

This figure is a heart-lung picture of the human thorax with the apex of the heart showing clearly on the left of the spinal column and the base stretching across the column, part of it showing distinctly on the right side opposite the apex

get for the cathode rays, which, being emitted at right angles to the concave surface of the cathode C, come to a focus at a point on the surface of this plate. This is the point at which the X rays are generated and from which they radiate in all directions. The target P is sometimes made of a heavy piece of tungsten.

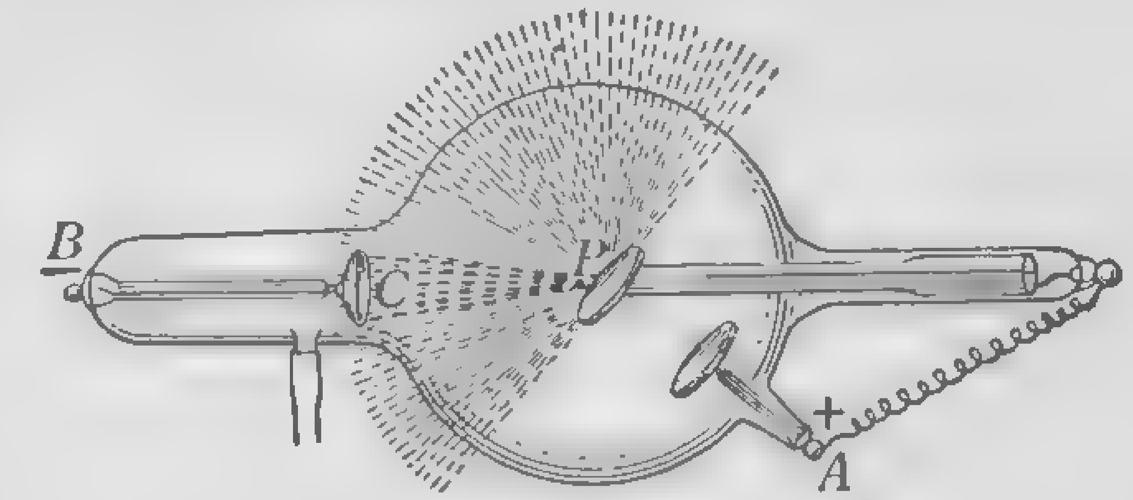


FIG. 482. An X-ray bulb

In order to convince oneself of the truth of this statement it is only necessary to observe an X-ray tube in action. It will be seen to be divided into two hemispheres by the plane which contains the platinum plate (see Fig. 482). The hemisphere which is facing the source of the X rays will be aglow with a greenish fluorescent light, whereas the other hemisphere, being screened from the rays, is darker. By moving a fluoroscope (a zinc-sulphide screen) about the tube it will be made evident that the rays which render the bones visible come from P.

496. Nature of X rays. Although X rays are like cathode rays in that they produce fluorescence, and also in that neither of them can be refracted or polarized, as light is, nevertheless they differ from cathode rays in several important respects. First, X rays penetrate many substances which are quite impervious to cathode rays; for example, they pass through the walls of the glass tube, whereas cathode rays ordinarily do not. Again, X rays are not deflected either by a magnet or by an electrostatic charge, nor do they carry electrical charges of any sort. Hence it is certain that they do not consist, like cathode rays, of streams of electrically charged particles.

It has recently been shown that X rays are extremely short waves similar to light waves but very much shorter, and of a variety of lengths. They are so short that the smoothest mirror we can manufacture is so rough in comparison with their length that it diffuses them. By taking advantage of the regular arrangement of the molecules in the faces of

crystals (mica, for example) a kind of reflection known as interference reflection is obtained when the X rays strike at certain favorable angles. Many of the X rays from an ordinary X-ray tube are so short that it would require 250,000,000 of them to make an inch. This represents a rate of vibration of 3,000,000,000,000,000,000 per second.

497. X rays render gases conducting. One of the notable properties which X rays possess in common with cathode rays is the property of causing any electrified body on which they fall slowly to lose its charge.

To demonstrate the existence of this property let any X-ray bulb be set in operation within 5 or 10 feet of a charged gold-leaf electroscope. The leaves at once begin to fall together.

The reason for this is that the X rays shake loose electrons from the atoms of the gas and thus fill it with positively and negatively charged particles, each negative particle being at the instant of separation an electron, and each positive particle an atom from which an electron has been detached. Any charged body in the gas therefore draws toward itself charges of sign opposite to its own, and thus becomes discharged.

498. X-ray pictures. The most striking property of X rays is their ability to pass through many substances which are wholly opaque to light, for example, cardboard, wood, leather, and flesh. Thus, if the hand is held close to a photographic plate and then exposed to X rays, a shadow picture of the denser portions of the hand, that is, the bones, is formed upon the plate. Opposite page 473 is shown an X-ray picture of the thorax of a living human being.

Rays somewhat like X rays but very much more penetrating and having a wave length not more than $\frac{1}{300}$ of the wave length of the shortest X rays have recently been found entering the earth in all directions from outer space.

Radioactivity

499. Discovery of radioactivity. In 1896 Henri Becquerel (see opposite page 478), in Paris, performed the following experiment: he wrapped a photographic plate in a piece of perfectly opaque black paper, laid a coin on top of the paper, and suspended above the coin a small quantity of the mineral uranium. He then set the whole away in a dark room and let it stand for several days. When he developed the photographic plate he found upon it a shadow picture of the coin similar to an X-ray picture. He concluded, therefore, that *uranium possesses the property of spontaneously emitting rays of some sort which have the power of penetrating opaque objects and of affecting photographic plates, just as X rays do.* He also found that these rays, which he called *uranium rays,* are like X rays in that they discharge electrically charged bodies on which they fall. He found also that the rays are emitted by all uranium compounds.

500. Radium. It was but a few months after Becquerel's discovery that Madame Curie (see opposite page 478), in Paris, began an investigation of all the known elements, to find whether any of the rest of them possessed the remarkable property which had been found to be possessed by uranium. She found that one of the remaining known elements, namely, thorium, the chief constituent of Welsbach mantles, is capable, together with its compounds, of producing the same effect. After this discovery the rays from all this class of substances began to be called *Becquerel rays,* and all substances which emitted such rays were called *radioactive* substances.

But in connection with this investigation Madame Curie noticed that pitchblende, the crude ore from which uranium is extracted, and which consists largely of uranium oxide, would discharge her electroscope about four times as fast as pure uranium. She inferred, therefore, that the radioactivity of pitchblende could not be owing entirely to the uranium

contained in it, and that pitchblende must therefore contain some hitherto unknown element which has the property of emitting Becquerel rays more powerfully than uranium or thorium. After a long and difficult search she succeeded in separating from several tons of pitchblende a few hundredths of a gram of a new element which was capable of discharging an electroscope more than a million times as rapidly as either uranium or thorium. She named this new element *radium.*

501. Nature of Becquerel rays. That these rays which are spontaneously emitted by radioactive substances are not X rays, in spite of their similarity in affecting a photographic plate, in causing fluorescence, and in discharging electrified bodies, is proved by the fact that they are found to be deflected by both magnetic and electric fields, and further by the fact that they impart electric charges to bodies upon which they fall. These facts constitute strong evidence that *radioactive substances eject from themselves electrically charged particles.*

But an experiment performed in 1899 by Rutherford (see opposite page 478), then of McGill University, Montreal, showed that Becquerel rays are complex, consisting of three different types of radiation, which he named the *alpha, beta,* and *gamma* rays. The beta rays are found to be identical in all respects with cathode rays; that is, *they are streams of electrons* projected with velocities varying from 60,000 to 180,000 miles per second. The alpha rays are distinguished from these by their very much smaller penetrating power, by their very much greater power of rendering gases conductors, by their very much smaller deflectibility in magnetic and electric fields, and by the fact that *the direction of the deflection is opposite to that of the beta rays.* From this last fact, discovered by Rutherford in 1903, the conclusion is drawn that the alpha rays consist of *positively* charged particles; and from the amount of their deflectibility their mass has been calculated to be about four times that of the hydrogen atom,— that is, about 7400 times the mass of the electron,— and their velocity to be about 20,000 miles per second.

Rutherford and Boltwood have collected the alpha particles in sufficient amount to identify them definitely as *positively charged atoms of helium.*

The difference in mass between the alpha and beta particles explains why the latter are so much more penetrating than the former, and why the former are so much more efficient than the latter in knocking electrons out of the molecules of a gas and rendering it conducting. A sheet of aluminum foil .005 centimeter thick cuts off completely the alpha rays but offers practically no obstruction to the passage of the beta and gamma rays.

The gamma rays are very much more penetrating than even the beta rays, and are not at all deflected by magnetic or electric fields. They are regular waves in the ether, like X rays, only shorter; and they are commonly supposed to be produced by the impact of the beta particles on surrounding matter.

502. Crookes's spinthariscope. In 1903 Sir William Crookes (see opposite page 390) devised a little instrument, called the spinthariscope, which furnishes very direct and striking evidence that particles are being continuously shot off from radium with enormous velocities. In the spinthariscope a tiny speck of radium R (Fig. 483) is placed about a millimeter above a zinc-sulphide screen S, and the latter is then viewed through a lens L, which gives from ten to twenty diameters magnification. The continuous soft glow of the screen, which is all one sees with the naked eye, is resolved by the lens into hundreds of tiny flashes of light. The appearance is as though the screen were being fiercely bombarded by an incessant rain of projectiles, each impact being marked by a flash of light, just as sparks fly from a flint when struck with steel. The experiment is a very beautiful one, and it furnishes very direct and convincing evidence that radium is continually projecting particles from itself at stupendous speeds. The flashes are due to the impacts of the *alpha,* not the *beta,* particles against the zinc-sulphide screen.

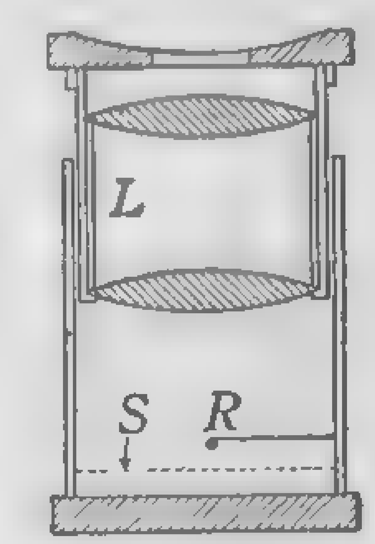


FIG. 483. Crookes's spinthariscope

A mixture composed of a radium compound and zinc sulphide glows constantly and is used for the dials of airplane instruments, compasses and watches, as well as on gun sights, making them visible for night use.

503. The disintegration of radioactive substances. Whatever is the cause of this ceaseless emission of particles exhibited by radioactive substances, it is certainly not due to any ordinary chemical reactions; for Madame Curie showed, when she discovered the activity of thorium, that the activity of all the radioactive substances is simply proportional to the amount of the active element present, and has nothing whatever to do with the nature of the chemical compound in which the element is found. Furthermore, radioactivity has been found to be independent of all *physical* as well as chemical conditions. The lowest temperature as well as the highest does not appear to affect it in the least. Radioactivity, therefore, is as unalterable a property of the atoms of radioactive substances as is weight itself. It is now known that the atoms of radioactive substances are disintegrating into simpler atoms. Uranium and thorium have the heaviest atoms of all the elements. For some unknown reason they seem not infrequently to become unstable and project off a part of their mass. This projected mass is the alpha particle. What is left of the atom after the explosion is a new substance with chemical properties different from those of the original atom. This new atom is, in general, also unstable and breaks down into something else. This process is repeated over and over again until some stable form of atom is reached. Somewhere in the course of this atomic catastrophe some electrons leave the mass; these are beta rays.

According to this point of view, which is now generally accepted, radium is simply one of the stages in the disintegration of the uranium atom. The atomic weight of uranium is 238; that of radium, about 226; that of helium, 4.00. Radium would then be uranium after the latter has lost 3 helium atoms. Uranium disintegrates very slowly. The time

WILLIAM CONRAD RÖNTGEN, MUNICH

Discoverer of X rays

ANTOINE HENRI BECQUEREL, PARIS

Discoverer of radioactivity

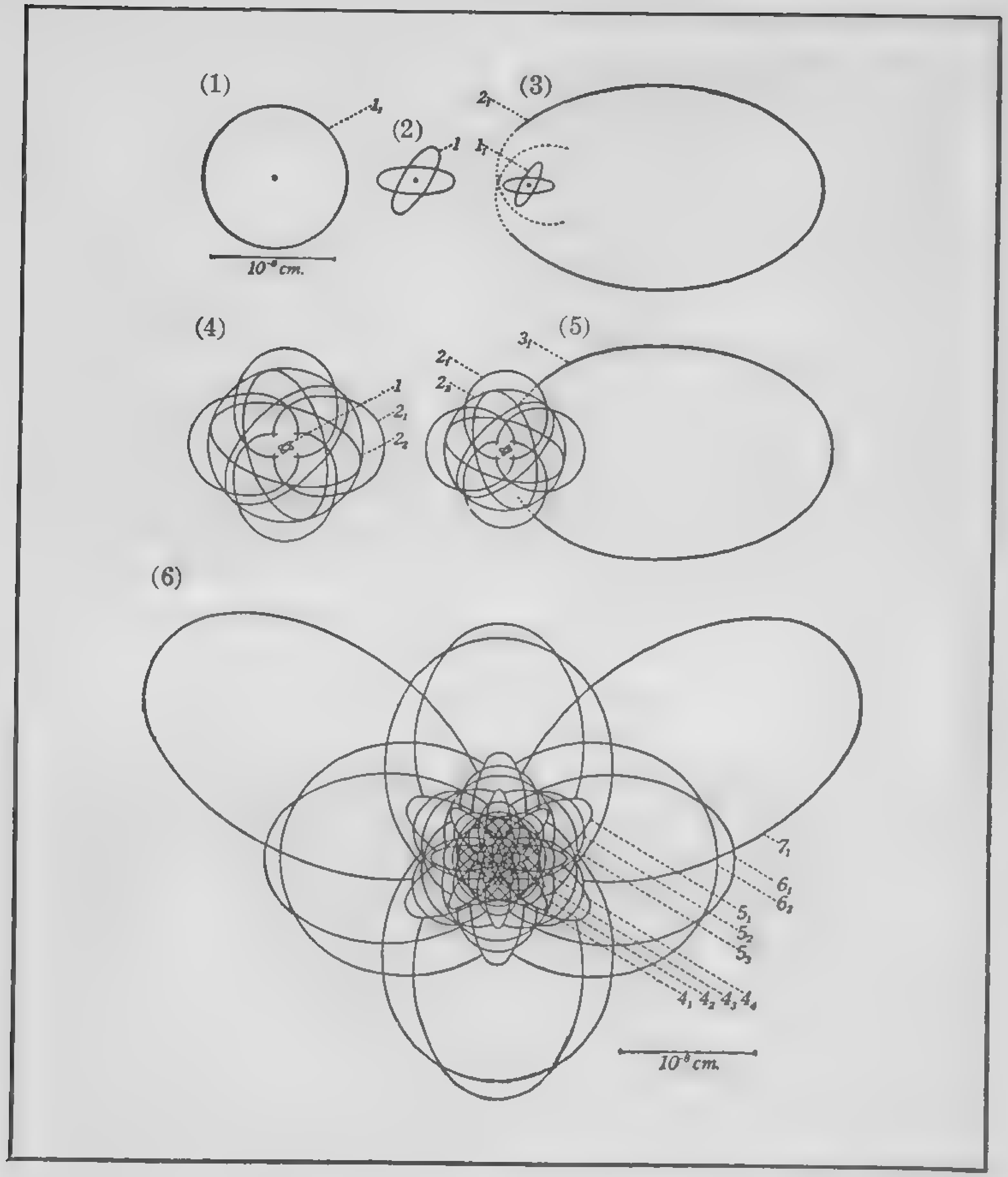
MADAME CURIE, UNIVERSITY OF PARIS

Discoverer of radium

E. RUTHERFORD, CAMBRIDGE UNIVERSITY (ENGLAND)

Discoverer of radioactive transformations

A GROUP OF MODERN PHYSICISTS



THE STRUCTURE OF ATOMS

That an atom consists of a positively charged center, or nucleus, containing an exact number of free, or unneutralized, positive charges varying by unit steps from 1 in the case of hydrogen to 92 in the case of uranium, with an exactly equal number of negative electrons held in the outer regions by the attraction of the positive electricity in the nucleus, is now universally recognized; that the negative electrons are rotating in orbits around the nucleus is extremely probable; of the shapes of these orbits little is known and still less of their orientations. The diagrams give hypothetical pictures of the paths of the satellite negative electrons about the central positive electronic nucleus in the cases of hydrogen (1), helium (2), lithium (3), neon (4), sodium (5), radium (6)

required for half of a given mass of uranium to disintegrate, the so-called *half-life,* is 4,500,000,000 years. There are four definite chemical products between uranium and radium, with half-lives successively of 23.8 days, 1.15 minutes, 2,000,000 years, and 90,000 years. The half-life of radium is 1580 years. Nine additional radioactive products have been identified in the succession following radium. The final product is lead, which is apparently stable. The half-life of the intervening substances ranges from about .000001 second for RaC′ to 16 years for RaD. Most of the others have a half-life of a few minutes or a few days.

504. Energy stored up in the atoms of the elements. In 1903 the two Frenchmen Curie and Labord made a discovery that was epoch-making. It was that radium is continually evolving heat at the rate of about 100 calories per gram per hour. More recent measurements have given 118 calories. This result was to have been anticipated from the fact that the particles which are continually flying off from the disintegrating radium atoms subject the whole mass to an incessant internal bombardment which would be expected to raise its temperature. This measurement of the exact amount of heat evolved per hour enables us to estimate how much heat energy is evolved in the disintegration of one gram of radium. It is about 2,000,000,000 calories — fully 300,000 times as much as is evolved in the combustion of one gram of coal. Furthermore, it is not impossible that similar enormous quantities of energy are locked up in the atoms of *all* substances, existing there perhaps in the form of the kinetic energy of rotation of the electrons. The most vitally interesting question which the physics of the future has to face is: Can man gain control of any such store of subatomic energy and use it commercially as a source of power? Such a result does not now seem likely or even possible; and yet the transformations which the study of physics has wrought in the world within a hundred years were once just as incredible as this.

The Growth of Physics in Thirty Years

505. Growing elements. Thirty years ago *the world was thought to be made of a certain number (70 odd) eternal unchangeable elements.* Today, through the discovery of radioactivity, the conception has been gained of a world which is continually evolving, even in its chemical elements; new elements, like lead, are formed continually out of old ones, like uranium and thorium, and these in their turn are presumably growing continually out of other elements somewhere in the universe.

506. Positive and negative electrons. Thirty years ago *electricity was not known to have an atomic structure.* Today it has been definitely proved to be made up of discrete particles, half positive and half negative, but all carrying exactly the same charge. The negatively charged particle is called the *electron.* It has been isolated and accurately measured in the United States and found to have a charge of 4.774×10^{-10} absolute electrostatic units. However, the mass, or inertia, of the positive electron (sometimes called the proton) is found to be 1845 times that of the negative electron; so practically the whole *mass* of every body is carried by the positive electrons contained in it.

507. Atomic numbers. Thirty years ago no one knew *how many different chemical elements there might be, nor did one know much about their physical relationships.* Today it is known quite definitely that there are in our world just 92 distinct chemical elements; for we have found a beautifully simple spectroscopic property which progresses by just 92 unit steps from the lightest element, hydrogen, to the heaviest, uranium, and we now know precisely what element fits into each step. The number of the step, between 1 and 92, to which an element belongs is called the *atomic number* of that element.

508. Structure of the atom. Thirty years ago no one knew anything about *the structure of the atom.* We now know that every atom contains a relatively heavy, but extraordinarily minute nucleus into which all its positive electrons are packed, the exact number of positive electrons being equal to the atomic weight. This number of positives is held together by a number of negatives within the nucleus equal to the atomic weight minus the atomic number. The atomic number is thus the number of free, or unneutralized, positives in the nucleus, and therefore also the number of negative electrons held in the outer regions of each atom by the unneutralized positives at the center, for each atom is as a whole electrically neutral. The volume of the nucleus is relatively a smaller part of the volume of the atom than is the volume of the sun of the solar system.

509. Electronic orbits. Thirty years ago no one knew anything about *the behavior of the electrons within the atom.* We now believe, though we do not know, that each of the negative electrons outside the nucleus is rotating in an orbit about it, much as the earth rotates about the sun. The number of such orbital electrons is then 1 in the hydrogen atom and 92 in uranium. These hypothetical orbits in a number of different atoms are shown opposite page 479.

510. Relations between ether waves and electrons. Thirty years ago we knew nothing whatever about *how the electrons act in the process of absorbing or emitting ether waves.* We now know that when an electron is jerked out of an atom by absorbing an ether wave of frequency ν it always has imparted to it a kinetic energy proportional to ν, or equal to $h\nu$; and reciprocally when an ether wave of frequency ν is emitted by an atom, the electrons within it fall in toward the nucleus just enough to make the difference in their energy before and after emission equal to $h\nu$.

511. Cosmic rays. Thirty years ago we knew nothing about *the existence of cosmic rays coming in to the earth in all directions from the depths of space,* and due to radioactive (that is, nuclear) changes of an energy value as high as that imparted to an electron in falling through 30,000,000 volts. Today

the existence of these mysterious super X rays that can pass through six feet of solid lead is a definitely established fact.

512. Practical value of physics. Thirty years ago no one had dreamed of any *practical application of present or future knowledge of electronic phenomena.* Today all our broadcasting, most of our wireless, nine tenths of all long-distance wire telephony, all our transmission of pictures by wire, and a host of other useful developments have resulted directly from that knowledge. In view of what physics has done, is doing, and yet can do for the progress of the world, can any-one be insensible either to its value or to its fascination?

APPENDIX

SUPPLEMENTARY QUESTIONS AND PROBLEMS

CHAPTER I. **1.** The 200-meter run at the Olympic games corresponds to the 220-yard run in our local games. Which is the longer and how much?

2. What is the weight in metric tons of a cube of lead 2 m. on an edge?

3. One kilogram of alcohol is poured into a cylindrical vessel and fills it to a depth of 8 cm. Find the cross section of the cylinder.

4. Find the length of a lead rod 1 cm. in diameter and weighing 1 kg.

5. A bottle filled with mercury weighed 700 g. The bottle empty weighed 20 g. Find the capacity of the bottle in cubic centimeters.

CHAPTER II. **1.** A swimming pool has a sloping bottom 75 ft. long and 30 ft. wide. The water is 9 ft. deep at one end and 4 ft. deep at the other. Find the total force on the bottom; on the end which measures 9 ft. by 30 ft.

2. Deep-sea fish have been caught in nets at a depth of a mile. How many pounds pressure are there to the square inch at this depth? (Specific gravity of sea water = 1.026.)

3. If the pressure at a tap on the first floor reads 80 lb. per square inch, and at a tap two floors above, 68 lb., what is the difference in feet between the levels of the two taps?

4. Forty years ago standpipes were generally straight cylinders. Today they are more commonly of the form shown in Fig. 484. What are the advantages of each form?

5. What pressure per square inch is required to force water to the top of the Woolworth Building in New York City, 780 ft. high?

6. If the vessel which is shown in Fig. 13 (1) (p. 18) has a base of 200 sq. cm. and if the water stands 100 cm. deep, what is the total force on the bottom?

7. If the weight of the empty vessel in Fig. 13 (1) is small compared with the weight of the contained water, will the force required to lift the vessel and water be greater or less than the force exerted by the water against the bottom? Explain.

FIG. 484. A water reservoir

8. A hydraulic press having a piston 1 in. in diameter exerts a force of 10,000 lb. when 10 lb. are applied to this piston. What is the diameter of the large piston?

9. The specific gravity of milk is 1.032. How would its specific gravity be affected by removing part of the cream? by adding water? May these two changes be made so as not to alter its specific gravity at all?

10. A stone has a weight of 300 g. and a volume of 90 cc. What is its apparent weight when submerged in kerosene having a specific gravity of .79?

11. A block of wood 15 cm. by 10 cm. by 4 cm. floats in water with 1 cm. in the air. Find the weight of the wood and its specific gravity.

CHAPTER III. 1. Explain the process of making air enter the lungs; of making lemonade rise in a straw.

2. If a circular piece of wet leather having a string attached to the middle is pressed down on a flat, smooth stone, as in Fig. 485, the latter may often be lifted by pulling on the string. Why do the stone and the leather not separate while you are lifting them?

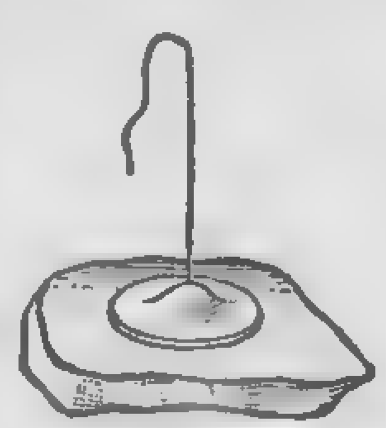


FIG. 485

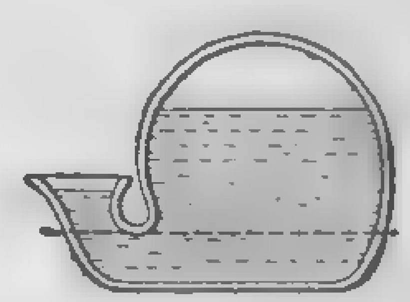


FIG. 486

3. Why does not the ink run out of a pneumatic inkstand like that shown in Fig. 486?

4. If a small quantity of air should get into the space at the top of the mercury column of a barometer, how would it affect the readings? Why?

5. If the pressure at a depth of 30 in. ($2\frac{1}{2}$ ft.) in mercury is 1 atmosphere, at what depth in feet would you expect the pressure of water to be 1 atmosphere? 2 atmospheres? 3 atmospheres? (Specific gravity of mercury = 13.6.)

6. Calculate the number of tons of atmospheric force on the roof of an apartment house 50 ft. × 100 ft. Why does the roof not cave in?

7. If Glaisher and Coxwell rose in their balloon until the barometric height was only 18 cm., how many inhalations were they obliged to make in order to obtain the same amount of air which they could obtain at the surface in one inhalation?

8. At the earth's surface 1 cc. of air weighs .00129 g. If this were the density all the way up, to what height in kilometers would the atmosphere extend? How many miles?

9. How high will a lift pump raise water if it is located upon the side of a mountain where the barometer reading is 71 cm.?

10. If a diver's tank has a volume of 2 cu. ft. and contains air under a pressure of 40 atmospheres, to what volume will the air expand when it is released at a depth of 34 ft. under water?

11. A gas tank having a capacity of 2 cu. ft. contained acetylene at a gauge pressure of 1845 lb. per square inch. When the gauge pressure got down to 915 lb. per square inch, how many cubic feet of the gas were used?

CHAPTER IV. 1. If a vessel with a small leak is filled with hydrogen at a pressure of 2 atmospheres, the pressure falls to 1 atmosphere about four times as fast as when the same experiment is tried with air. Can you see a reason for this?

2. Find the pressure to which the diver was subjected who descended to a depth of 304 ft. Find the density of the air in his suit, the density at the surface being .00128 g. per cubic centimeter and the temperature being assumed to remain constant. Take the pressure at the surface as 30 in.

CHAPTER V. 1. A cake of ice weighing 200 lb. is held at rest upon an inclined plane 12 ft. long and 3 ft. high. By the resolution-and-proportion method find the component of its weight that tends to make the ice slide down the incline. With what force must one push to keep the ice at rest? How great is the component that tends to break the incline?

2. A boy pulls a loaded sled weighing 200 lb. up a hill which rises 1 ft. in 5 measured along the slope. Neglecting friction, how much force must he exert?

3. A man was let down over a cliff on a rope 500 ft. What was his period as a pendulum?

4. Explain why the toy in Fig. 487 will not lie upon its side, but rises to the vertical position. Does the center of gravity rise?

5. Where is the center of gravity of a hoop? of a cubical box? Is the latter more stable when empty or when full? Why?

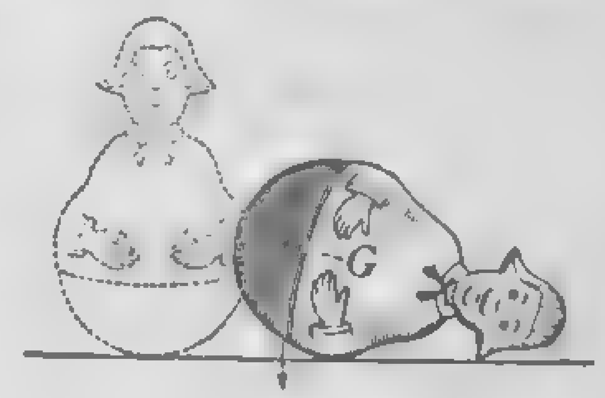


FIG. 487

6. Where must the center of gravity of the beam of a balance be with reference to the supporting knife-edge C? (Fig. 5, p. 6.) Why? Could you make a weighing if C and g coincided? Why?

7. A body starting from rest and moving with uniformly accelerated motion acquired a velocity of 60 ft. per second in 5 sec. Find (1) the acceleration; (2) the average velocity during the 5 sec.; (3) the total distance traversed in 5 sec.

8. How long will it take a trolley car starting from rest with an acceleration of 2.5 ft./sec.^{2} to travel 100 ft.?

9. A ball shot straight upward near a pond was seen to strike the water in 10 sec. How high did it rise? What was its initial speed?

10. What force supports an airplane in flight?

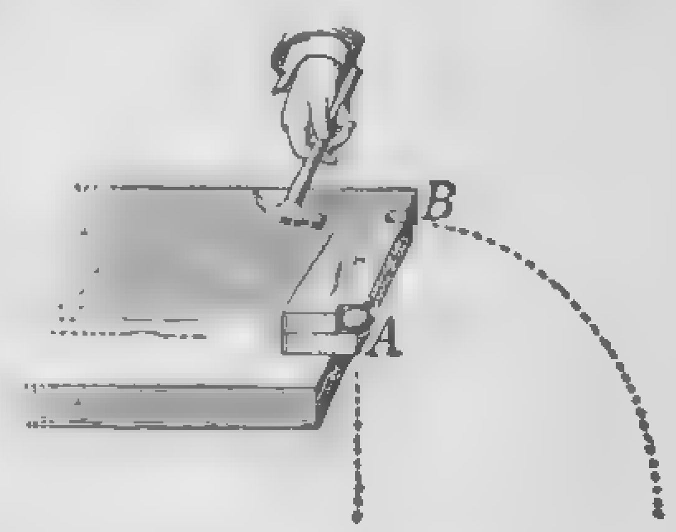


FIG. 488

11. If a weight is dropped from the roof to the floor of a moving car, will it strike the point on the floor which was directly beneath its starting point?

12. If one ball is thrown horizontally from the top of a tower and another dropped at the same instant, which will strike the earth first? (Remember that the acceleration produced by a force is in the direction in which the force acts and proportional to it, whether the body is at rest or in motion. See second law.) If possible, try the experiment with an arrangement like that of Fig. 488.

13. A bombing airplane is flying 60 mi. per hour in still air at a height of 1600 ft. In order to score a bull's-eye, at what distance in advance of the target must the bomb be let go?

14. If a 10-gram bullet is shot from a 5-kilogram gun with a speed of 400 m. per second, what is the backward speed of the gun?

15. If a team of horses pulls 500 lb. in drawing a wagon, with what force does the wagon pull backward upon the team? Why do the wheels turn before the hoofs of the horses slide?

16. Why does a falling apple in striking your head exert a force in excess of its weight?

CHAPTER VI. 1. A wire which is twice as thick as another of similar material will support how many times as much weight?

2. What must be the cross section of a wire of copper if it is to have the same tensile strength (that is, break with the same weight) as a wire of iron 1 sq. mm. in cross section? (See § 109.)

3. Tell how you may, by use of Hooke's law and a 20-pound weight, make the scale for a 32-pound spring balance.

4. Explain how capillary attraction comes usefully into play in the steel pen, camel's-hair brushes, lamp wicks, and sponges.

5. Fasten a bit of gum camphor to one end of half a toothpick and lay it upon the surface of a large vessel of clean still water. Explain the motion.

6. How can you tell whether bubbles which rise from the bottom of a vessel which is being heated are bubbles of air or bubbles of steam?

CHAPTER VII. 1. A steel bar of uniform cross section is 20 ft. long and weighs 100 lb. How much work is required to lift it from a horizontal to a vertical position, one end being kept always on the ground?

2. If the 20,000 inhabitants of a city use an average of 20 l. of water per capita per day, how many kilogram meters of work must the engines do per day if the water has to be raised to a height of 75 m.?

3. How would you arrange a crowbar to use as a lever of the first class in overturning a heavy object? as a lever of the second class?

4. A uniform plank 20 ft. long, weighing 200 lb., rests on a flat roof with 8 ft. of its length projecting beyond the edge of the roof. If a keg of nails weighing 50 lb. rests over a point 1 ft. from the inner end, how far out on the plank beyond the edge of the roof may a man weighing 180 lb. go without tipping the plank?

5. If the ball of the float valve (Fig. 489) has a diameter of 10 cm. and if the distance from the center of the ball to the pivot

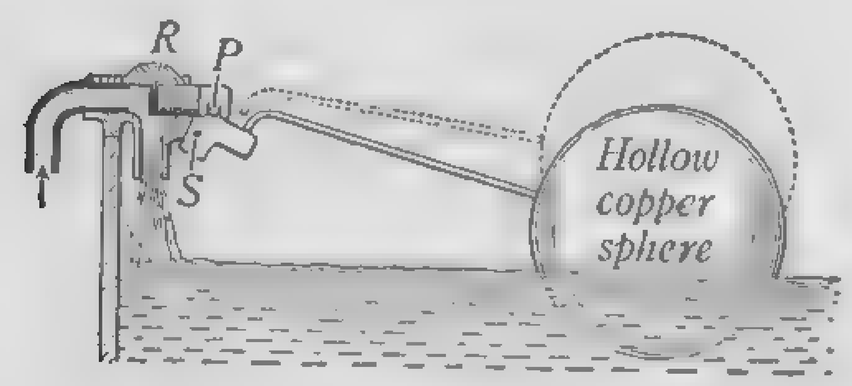


FIG. 489

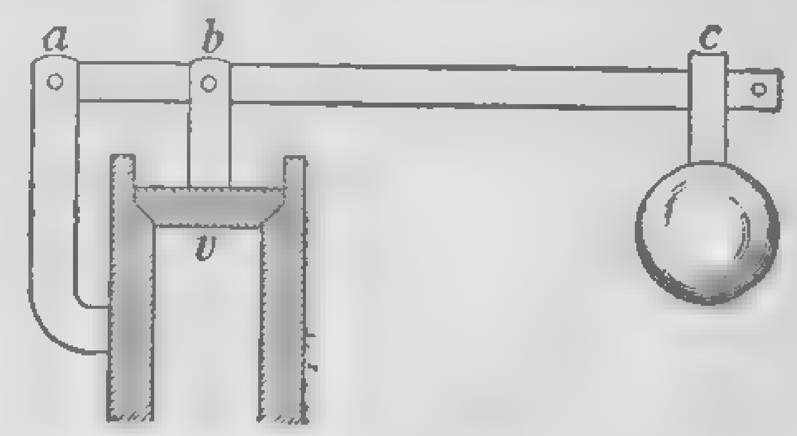


FIG. 490

S is 20 times the distance from S to the pin P, with what force is the valve R held shut when the ball is half immersed? (Neglect weight of ball.) (Volume of a sphere $= \frac{4}{3}\pi r^3$.)

6. A safety valve and weight are arranged as in Fig. 490. If ab is $1\frac{1}{2}$ in. and bc $10\frac{1}{2}$ in., what effective steam pressure per square inch is required on the valve to unseat it, if the area of the valve is $\frac{1}{2}$ sq. in. and the weight of the ball 4 lb.?

7. The hay scales shown in Fig. 491 consist of a compound lever with fulcrums at F, F', F'', F'''. If Fo and $F'o'$ are lengths of 6 in., FE and $F'E$ 5 ft., $F''n$ 1 ft., $F''m$ 6 ft., rF''' 2 in., and $F'''S$ 20 in., how many pounds at W will be required to balance a weight of a ton on the platform?

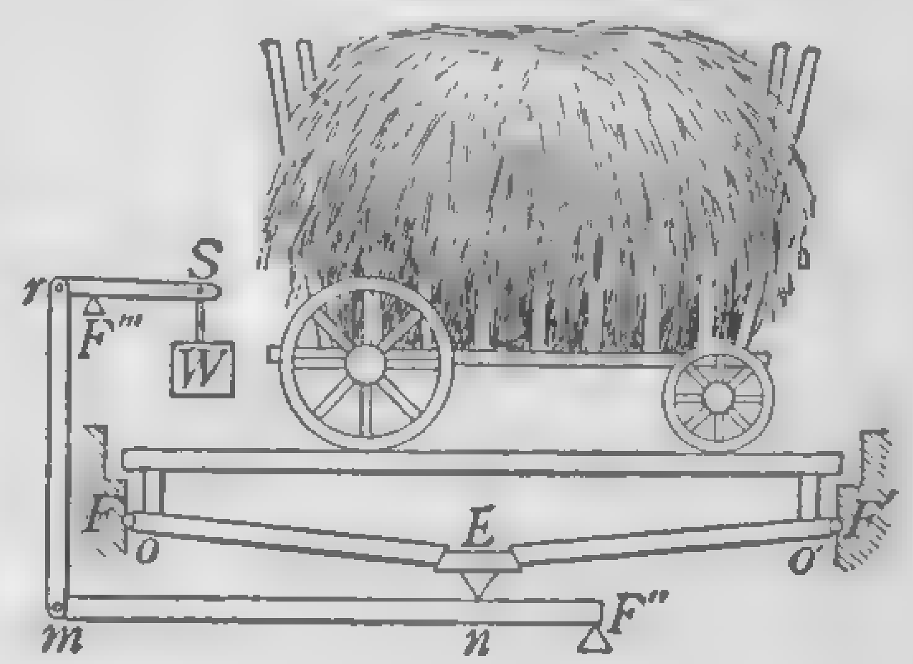


FIG. 491

8. If in the crane of Fig. 492 the crank arm has a length of $\frac{1}{2}$ m., and the gear wheels, A, B, C, and D have respectively 12, 48, 12, and 60 cogs, and the axle over which the chain runs has a radius of 10 cm., what is the mechanical advantage of the crane?

9. A man weighing 198 lb. walked up the stairway of the Washington Monument (500 ft. high) in 10 min. At what power did

he work in foot pounds per minute? At what horse power? If he had gone up in 20 min., what would have been the power?

10. A cannon ball is moving at a height of 4 mi. with a speed of 1600 ft. per sec. If the weight of the projectile is 1000 lb., how much kinetic energy has it? how much potential energy? (Calculate your results in foot pounds.)

11. A 2000-barrel water tank at 40 ft. mean elevation is to be filled with water. Assuming a barrel of water to weigh 260 lb., how much work is required to fill the tank? If the work is done by a motor-driven pump working at the rate of 4 H.P., how many minutes are required to fill the tank?

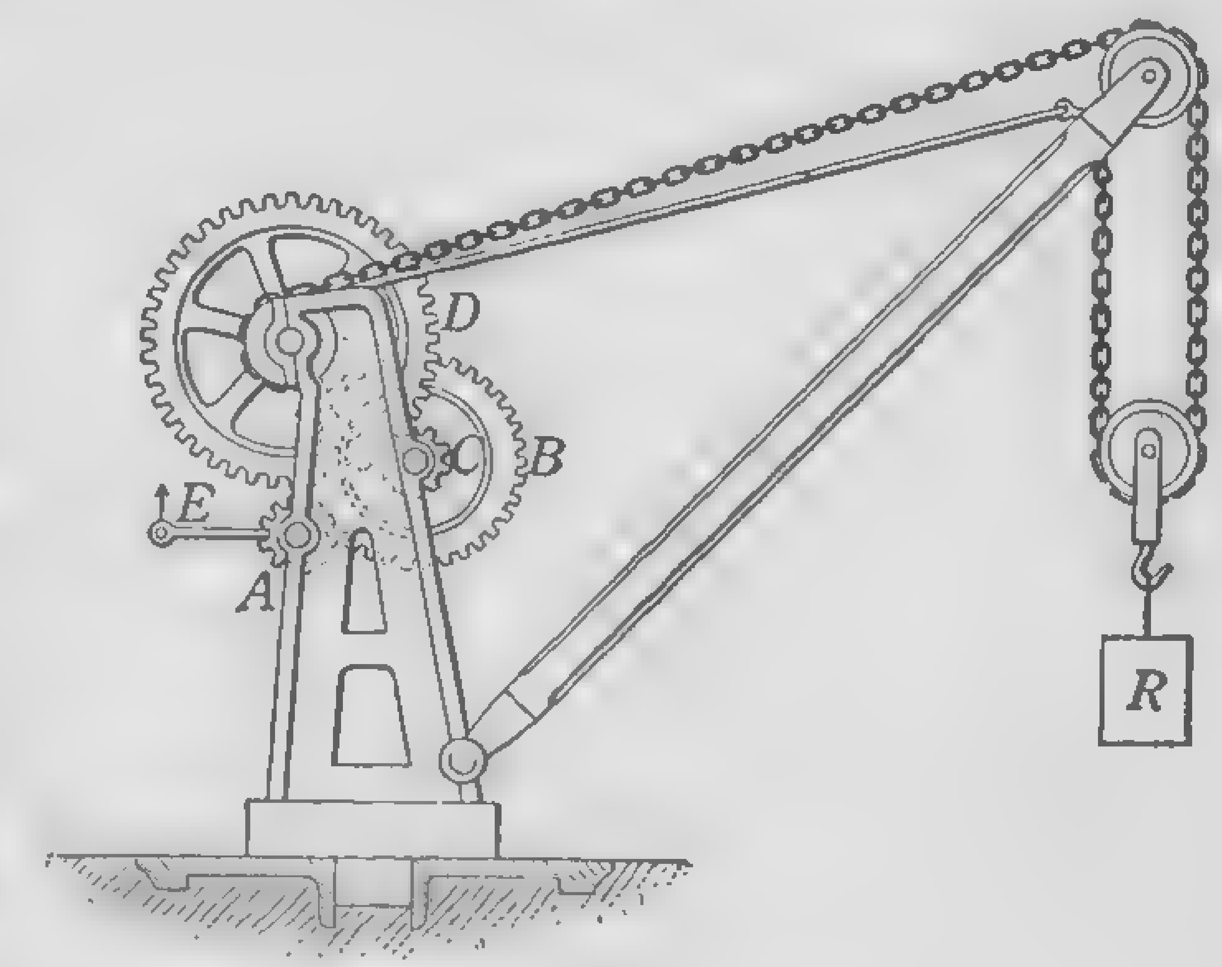


FIG. 492. The crane

12. What is the force of the backward thrust of the propeller of an airplane driven by an engine developing 150 H.P. when the airplane is traveling 120 mi. per hour?

13. A smooth block is $10 \times 8 \times 3$ in. Compare the distances which it will slide when given a certain initial velocity on smooth ice if resting on a 10×8 face; on a 10×3 face; on an 8×3 face.

14. Turbines at Niagara have a horse power of 70,000 and an efficiency of 93 per cent. The head of water is 213.5 ft. How many cubic feet of water does each turbine discharge per minute?

15. If it is necessary to pull on a block and tackle with a force of 100 lb. in order to lift a weight of 300 lb., and if the force must move 6 ft. to raise the weight 1 ft., what is the efficiency of the system?

16. Over a waterfall 22 ft. high flows 450 cu. ft. of water each second. What H.P. could be developed if all the water were utilized by a water wheel having an efficiency of 80 per cent?

CHAPTER VIII. **1.** The normal temperature of the body is 98.6° F. What is its centigrade?

2. Two thermometers have bulbs of equal size. The bore of one has a diameter twice that of the other. What are the relative lengths of the stems between 0° and 100°?

3. An automobile tire contained air under a pressure of 70 lb. per square inch at a temperature of 20°C. On being driven, the temperature of the air rose to 35°C. What was the increase in pressure within the tire?

4. Two liters of air at atmospheric pressure and at 20°C. are heated until the volume and the pressure are both doubled. What is the temperature of the air?

5. When the bulb of a thermometer is placed in hot water, the mercury at first falls a trifle and then rises. Why?

6. Show from equation (5), p. 158, that linear coefficient of expansion may be defined as *increase in length per unit length per degree.*

7. If a surveyor's steel tape is exactly 100 ft. long at 20° C., how much too short would it be at 0° C.?

8. If the variation of temperature throughout the year is 50° C., what space must be left between the ends of steel railroad rails laid in the coldest part of the year?

CHAPTER IX. **1.** Meteorites are small, cold bodies moving about in space. Why do they become luminous when they enter the earth's atmosphere?

2. Analyze the transformations of energy which occur when a bullet is fired vertically upward.

3. Show that the energy of a waterfall is merely transformed solar energy.

4. In an experimental determination of the mechanical equivalent of heat it was estimated that the temperature of 100 g. of water was raised 5.85° C. by the work done by a mass of 10 kg. falling 25 m. Calculate the mechanical equivalent of heat.

5. How many B.T.U. are required to warm a 6-pound laundry iron from 75° F. to 250° F.?

6. Eight pounds of water were placed in a copper kettle weighing 2.5 lb. How many B.T.U. are required to heat the water and the kettle from 70° F. to 212° F.? If 4.3 cu. ft. of gas is used to do this, and if each cubic foot of gas on being burned yields 600 B.T.U., what is the efficiency of the heating apparatus?

7. A copper calorimeter of mass 200 g. contains 150 g. of water at 8° C.; 300 g. of lead shot are transferred to the calorimeter from a cup which has been immersed for some time in boiling water. What temperature do the calorimeter and water attain?

8. A copper ball weighing 3 kg. was heated to a temperature of 100° C. When placed in water at 15° C. it raised the temperature to 25° C. How many grams of water were there?

9. If the specific heat of lead is .031 and the mechanical equivalent of a calorie 427 g. m., through how many degrees centigrade will a 1000-gram lead ball be raised if it falls from a height of 100 m., provided all the heat developed by the impact goes into the lead?

CHAPTER X. **1.** What is the temperature of a mixture of ice and water? What determines whether it is freezing or melting?

2. Just what will occur if 1000 calories be applied to 20 g. of ice at 0° C.?

3. How many grams of ice must be put into 200 g. of water at 40° C. to lower the temperature 10° C.?

4. Why are icebergs frequently surrounded with fog?

5. A morning fog generally disappears before noon. Explain the reason for its disappearance.

6. Why will an open, narrow-necked bottle containing ether not show as low a temperature as an open shallow dish containing the same amount of ether?

7. What weight of water is contained in a room 5 × 5 × 3 m. if the relative humidity is 60 per cent and the temperature 20° C.? (See table, p. 183.)

8. How many calories are given up by 30 g. of steam at 100° C. in condensing and then cooling to 20° C.? How much water will this steam raise from 10° C. to 20° C.?

9. How many times as much heat is required to convert any weight of water at 100° C. into steam as to warm an equal weight of water 1° C.? 1° F.? How many B.T.U. are required to convert 1 lb. of water at 212° F. into steam? How many foot pounds of mechanical energy are equivalent to this amount of heat energy?

10. How many B.T.U. are liberated within a radiator when 10 lb. of steam condense there?

11. Why does the distillation of a mixture of alcohol and water always result to some extent in a mixture of alcohol and water?

12. When part of the salt water in a vessel freezes, the ice formed is free from salt. What effect, then, does freezing have on the concentration of the remaining salt solution?

13. A partially concentrated salt solution which has a freezing point of $-5°$ C. is placed in a room which is kept at $-10°$ C. Will it all freeze?

14. How many foot pounds of energy are there in 1 lb. of coal containing 14,000 B.T.U. per pound? How many pounds of iron must be held at a height of 150 ft. to have as much energy as this pound of coal?

15. The average locomotive has an efficiency of about 9 per cent. What horse power does it develop when it is consuming 1 t. of coal per hour? (See problem 14, above.)

CHAPTER XI. 1. If a piece of paper is wrapped tightly around a metal rod and held for an instant in a Bunsen flame, it will not be scorched. If held in a flame when wrapped around a wooden rod, it will be scorched at once. Explain.

2. If one touches the pan containing a loaf of bread in a hot oven, he receives a much more severe burn than if he touches the bread itself, although the two are at the same temperature. Explain.

3. Why are plants often covered with paper on a night when frost is expected?

4. If you open a door between a warm and a cold room, in what direction will a candle flame be blown which is placed at the top of the door? Explain.

5. Why should steam radiators be installed on the cold side of a room; for example, near outside walls or windows?

6. Name the essential parts for each of three different systems commonly employed for heating houses, and state the physical principles applied in each case which render it effective.

7. If 2 metric tons of coal are burned per month in your house, and if your furnace allows one third of the heat to go up the chimney, how many calories remain to be used per day? (Take 1 g. as yielding 6000 calories. A metric ton = 1000 kg.)

CHAPTER XII. 1. Do the facts of induction suggest to you any reason why a horseshoe magnet retains its magnetism better when a bar of soft iron (a keeper, or armature) is placed across its poles than when it is not so treated? (See Fig. 216.)

2. A magnetic pole of 80 units' strength is 20 cm. distant from a similar pole of 30 units' strength. Find the force between them.

3. Why should the needle used in the experiment of § 276 be placed east and west, when adjusting for neutral equilibrium, before it is magnetized?

4. If a bar magnet is floated on a piece of cork, will it tend to float toward the north? Why? Try it.

5. The dipping needle is suspended from one arm of a steel-free balance and carefully weighed. It is then magnetized. Will its apparent weight increase? Try it.

6. How would an ordinary compass needle act if placed over one of the earth's magnetic poles? How would a dipping needle act at these points?

7. From the map find the declination in the vicinity of Maine; of California.

8. Why, in general, are the tops of radiators throughout the United States *S* magnetic poles, as shown by their repelling of the *S* pole of a compass? What, in general, is the polarity of the tops of radiators in South America?

CHAPTER XIII. 1. Why is repulsion between an unknown body and an electrified pith ball a surer sign that the unknown body is electrified than is attraction?

2. If you charge an electroscope and then bring your hand toward the knob (not touching it), the leaves go closer together. Why?

3. If you bring a positively charged glass rod near the knob of an electroscope and then touch the knob, why do you not remove the negative electricity which is on the knob?

4. If you are given a positively charged insulated sphere, how could you charge two other spheres, one positively and the other negatively, without diminishing the charge on the first sphere?

5. Two small spheres are charged with + 16 and − 4 units of electricity. With what force will they attract each other when at a distance of 4 cm.?

6. By reference to Fig. 244 explain how a Wimshurst machine builds up a large + charge in one jar and a correspondingly large − charge in the other.

CHAPTER XIV. 1. A current is passed through two electrolytic cells connected in series. One cell contains copper electrodes in a solution of copper sulphate, and in the other cell there are platinum electrodes in a solution of sulphuric acid. Describe the phenomena which take place at each of the four electrodes.

2. If 6.7 g. of silver are deposited on the cathode in an electrolytic plant in one minute when a current of 100 amperes is used, what is the electrochemical equivalent of silver?

3. How long will it take a current of 1 ampere to deposit 1 g. of silver from a solution of silver nitrate?

4. If the same current used in problem 3 were led through a solution containing a zinc salt, how much zinc would be deposited in the same time?

5. The coulomb (§ 306) is 3 billion times as large as the electrostatic unit of quantity defined in § 280. How many electrons pass per second by a given point on a lamp filament which is carrying 1 ampere of current (see § 284)?

6. If the earth's magnetism is due to a surface charge rotating with the earth, must this charge be positive or negative in order to produce the sort of magnetic poles which the earth has? (This is actually the present theory of the earth's magnetism.)

7. The E.M.F. of a certain battery is 10 volts and the strength of the current obtained through an external resistance of 4 ohms is 1.25 amperes. What is the internal resistance of the battery?

8. Can you prove from a consideration of Ohm's law that when wires of different resistances are inserted in series in a circuit the P.D.'s between the ends of the various wires are proportional to the resistances of these wires?

9. Why is it desirable that an ammeter, which is used in the circuit in series for measuring currents, have as low a resistance as possible?

10. A storage battery of 60 cells arranged in series is used to light 10 incandescent lamps arranged in parallel. Each lamp has a hot resistance of 190 ohms, each cell of .01 ohm and the mains have a resistance of .4 ohm. The E.M.F. of each cell is 2 volts. What current flows (1) from the battery? (2) through each lamp?

11. Three dry cells (each having an E.M.F. of 1.5 volts) are joined in series to light 5 little lamps in parallel. What strength of current flows from the cells, the resistance of each cell being .1 ohm and of each lamp 6 ohms?

12. An electric soldering iron allows 5 amperes to flow through it when connected to an E.M.F. of 110 volts. What will it cost, at $.12 per kilowatt hour, to operate the iron 6 hr. per day for 5 da.?

13. A current of electricity passed through a coil of wire having a resistance of 10 ohms heated 1000 g. of water from 15° C. to 61.08° C. in 5 min. What was the strength of the current?

14. At a cost of $.04 per kilowatt hour how much will it cost per week of 48 hr. to run a motor having an average load of 35 H.P. and an average efficiency of 85 per cent? (One horse power = 746 watts.)

CHAPTER XV. 1. If a series-wound dynamo is running at a constant speed, what effect will be produced on the strength of the field magnets by diminishing the external resistance and thus increasing the current? What will be the effect on the E.M.F.? (Remember that the whole current goes around the field magnets.) (See § 358.)

2. If a shunt-wound dynamo is run at constant speed, what effect will be produced on the strength of the field magnets by reducing the external resistance? What effect will this have on the E.M.F.?

3. In an incandescent-lighting system the lamps are connected in parallel across the mains. Every lamp which is turned on, then, diminishes the external resistance. Explain from a consideration of problems 1 and 2 why a compound-wound dynamo (Fig. 321) keeps the P.D. between the mains constant.

4. With the aid of the dynamo rule explain why, in Figs. 317 and 319, the current in the conductors under the north poles is moving toward the observer and that in the conductors under the south poles away from the observer.

5. When an electric fan is first started, the current through it is much greater than it is after the fan has attained its normal speed. Why?

6. A motor takes 8 amperes from a 500-volt circuit and delivers 5 H.P. What is its efficiency?

7. If a current is sent into the armature of Fig. 317 at b', and taken out at b, which way will the armature revolve?

8. Show that if the reverse of Lenz's law were true, a motor once started would run of itself and do work; that is, it would furnish a case of perpetual motion.

9. Does the spark of an induction coil occur at make or at break? Why?

10. Why could not an armature core be made of coaxial cylinders of iron running the full length of the armature, instead of flat disks, as shown in Fig. 330?

11. A transformer is so wound as to step the voltage of the lighting circuit from 2200 volts down to 110. Sketch the transformer and its connections, marking the primary and the secondary, and state the relative number of turns in each. If the house circuit uses 40 amperes, what current must flow in the primary?

CHAPTER XVI. 1. Stations A, B, and C are one mile apart in a straight line. An enemy's cannon is heard at A and C at the same instant, but two seconds sooner at B. Locate the cannon with reference to these three points, temperature 20° C.

2. A bullet fired from a rifle with a speed of 1200 ft. per second is heard to strike the target 6 sec. afterwards. What is the distance to the target, the temperature of the air being 20° C.? (Let $x =$ the distance to the target.)

3. How would the intensity of the sound of a bell heard by a man 1000 feet away compare with the intensity of the sound heard by a man 2000 feet away if no reflections of the sound took place?

4. Why does placing the hand back of the ear enable a partially deaf person to hear better?

5. If the lowest tone which the ear can recognize has a frequency of 16 vibrations per second, what is the length of the longest wave the ear perceives in air at a temperature of 0° C.?

6. The sound of a tuning fork is reënforced when held over a closed air column 4 in. long, and the next position of resonance occurs when the air column is 12 in. long. Find the frequency of the fork, temperature 20° C.

7. A man riding on an express train moving at the rate of 1 mi. per minute hears a bell ringing in a tower in front of him. If the bell makes 280 vibrations per second, how many pulses will strike his ear per second, the velocity of sound being 1120 ft. per second? (The number of extra impulses received per second by the ear is equal to the number of wave lengths contained in the distance traveled per second by the train.) What effect has this upon the pitch? Had he been going from the bell at this rate, how many pulses per second would have reached his ear? How would this affect the pitch?

8. A tuning fork gives strong resonance when held on its flat side or on its edge, but when held cornerwise over the air column the resonance ceases. Explain.

CHAPTER XVII. 1. What is the pitch of a note whose wave length is 5.4 in., the speed being 1152 ft. per second?

2. Two strings, each 6 ft. long, make 256 vibrations per second. If one of the strings is lengthened 1 in., how many beats per second will be heard?

3. If a vibrating string is found to produce the note C when stretched by a force of 10 lb., what must be the force exerted to cause it to produce (1) the note E? (2) the note G?

4. What must be the length of a closed organ pipe which produces the note E? (Take the speed of sound as 340 m. per second.)

5. What is the first overtone which can be produced in an open G organ pipe?

6. What is the first overtone which can be produced by a closed G organ pipe?

CHAPTER XVIII. 1. The earth reflects sixteen times as much light to the moon as the moon does to the earth. Trace from the sun to the eye of the observer the light by which he is able to see the dark part of the new moon. Why can we not see the dark part of a third-quarter moon?

2. If the word "white" be painted with white paint (or whiting moistened with alcohol) across the face of a mirror and held in the

path of a beam of sunlight in a darkened room, in the middle of the spot on the wall which receives the reflected beam the word "white" will appear in black letters. Explain.

3. The diameter of the moon is 2000 mi. and that of the sun 860,000 mi., and the sun is 93,000,000 mi. away. What is the length of the moon's umbra?

4. If the distance from the center of the earth to the center of the moon were exactly equal to the length of the moon's umbra, over how wide a strip on the earth's surface would the sun be totally eclipsed at any one time?

5. Look at the reflected image of an electric-light filament in a piece of red glass. Why are there two images, one red and one white?

6. If a 4-candle-power light at a distance of 1 ft. gives enough illumination for reading, how far away must a 64-candle-power lamp be placed to make the same illumination? How strong a lamp should be used at a distance of 8 ft. from the book?

7. If the page of your book is sufficiently illuminated at a distance of 3 ft. from a 20-candle-power lamp, how many candle power will be needed when you move 2 ft. farther away?

8. The moon has practically no atmosphere. We know this because when a star appears to pass behind the moon there is no decrease or increase in its apparent velocity while disappearing or coming into view again. If the moon had an atmosphere like that of the earth, explain how this would affect the apparent velocity of the star at both these times.

9. Does a man above the surface of water appear to a fish to be farther from the surface than he actually is or nearer to it? Make an explanatory wave diagram.

10. When light passes obliquely from air into carbon bisulphide it is bent more than when it passes from air into water at the same angle. Is the speed of light in carbon bisulphide greater or less than in water?

CHAPTER XIX. 1. It is desired to enlarge a 2.5 by 4.5 inch photograph to 10 by 18 inches. If the distance between the original photograph and the enlarged image is 40 inches, what must be the focal length of the lens used?

2. If a rose R is pinned upside down in a brightly illuminated box, a real image may be formed in a glass of water W by a concave mirror C (Fig. 493). Where must the eye be placed to see the image?

3. How far is the rose from the mirror in the arrangement of Fig. 493?

4. (1) What should be the focal length of the lens of a camera designed to photograph distant objects on a film 6 ft. behind the lens? (2) How far from the film should this lens be placed to properly focus an object distant 10 ft. from the lens?

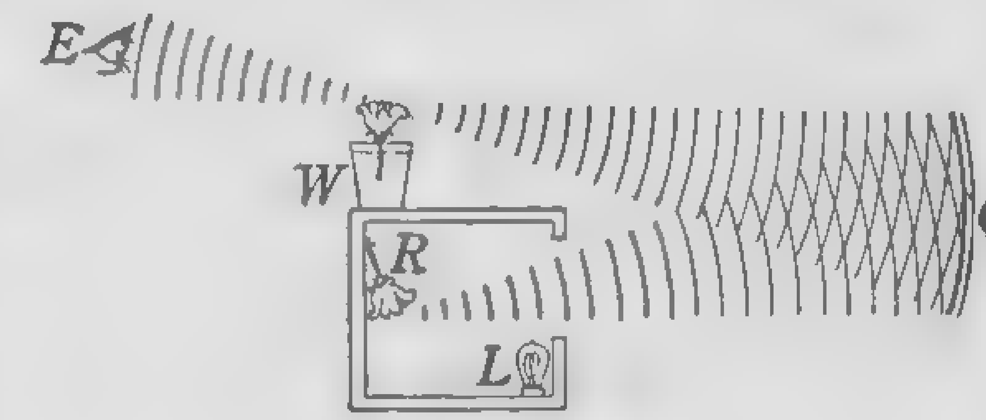


FIG. 493

5. A child 3 ft. in height stood 15 ft. from a camera whose lens had a focal length of 18 in. What was the distance from the lens to the photographic plate and the length of the child's photograph?

6. The image, on retina, of a book held a foot from the eye is larger than that of a house on the opposite side of the street. Why do we not judge that the book is actually larger than the house?

7. Explain as well as you can how a telescope forms the image that you see when you look through it.

8. A compound microscope has a tube length of 8 in., an objective of focal length $\frac{1}{2}$ in., and an eyepiece of focal length 1 in. What is its magnifying power?

9. If the focal length of the eye is 1 in., what is the magnifying power of an opera glass whose objective has a focal length of 4 in.?

10. The parabolic mirror used as an objective in one of the telescopes at the Mt. Wilson Observatory is 100 in. in diameter and has a focal length of about 50 ft. What magnification is obtained when it is used with a 2-inch eyepiece; with a 1-inch eyepiece? What is gained by the use of a mirror of such enormous diameter?

CHAPTER XX. 1. Is the index of refraction of glass the same for red light as for green light? Give reason for your answer.

2. If the velocity of light is 186,000 mi. per second, what is the velocity of yellow light through a diamond, a substance whose index of refraction for yellow light is 2.47?

3. Explain the ghastly appearance of the face of one who stands under the light of a Cooper-Hewitt mercury-vapor arc lamp.

4. Can you see any reason why the vibrating molecules of an incandescent gas might be expected to give out a few definite wave lengths, whereas the particles of an incandescent solid give out all possible wave lengths?

5. Can you see any reason why it is necessary to have the slit narrow and the slit and screen at conjugate foci of the lens in order to show the Fraunhofer lines in the experiment of § 477?

6. If a soap film is illuminated with red, green, and yellow strips of light, side by side, how will the distance between the yellow fringes compare with that between the red fringes? with that between the green fringes? (See table on page 435.)

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